The field of municipal street and outdoor lighting has been undergoing significant change for some time now. Not least the introduction of LED lighting has completely revitalized the development of new luminaires, electronic control gear and components. However, many decision makers with responsibility for lighting will find the huge array of products on the market as well as the associated flood of technical data quite challenging. The only way to assess the numerous different claims is to acquire dependable expert knowledge on the topic. This technical street and outdoor lighting manual is designed to assist users in the process of obtaining an overview of the current state of the art.

A select group of lighting industry experts and users of lighting technology has contributed to this book with the aim of explaining the complex topic of lighting. It is designed to support employees of municipal utility companies, representatives of town councils as well as planning and engineering companies in making decisions regarding current projects.

Frank Bodenhaupt · Frank Lindemuth (ed.)
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editors

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Frank Lindemuth
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Preface by the editors

The task of municipal street lighting includes making a contribution towards traffic safety on roads during the dark hours of the day. With the aim of increasing the personal safety of citizens, sufficient street lighting must be provided as a precautionary measure against criminal assaults. A further goal pursued by the provision of appropriate street lighting is to increase the attractiveness of and revitalise inner city areas. In short, street lighting improves the quality of life for the entire population.

The quest towards greater cost and energy efficiency, alongside eco-compatibility and a need to reshuffle public spending budgets, no longer needs to stand in conflict with the aims pursued by street lighting. For many years, many town and rural councils felt forced to reduce street lighting during the night or even to switch it off altogether due to financial constraints – a fact that also mirrors a sense of powerlessness felt by many councils. Although such measures certainly helped to reduce public spending for the short term, switching off street lighting exerts a negative influence on many areas of society over the long term. Not only does the risk of accidents increase, but the quality of life and the attractiveness of a city decline as well.

At the same time, new technologies are gaining ground in the field of street lighting – technologies with which both users and operators have to keep pace. But the sheer number of such new developments is making it increasingly difficult to keep track. The manner in which luminaires, ballasts, control options and energy supply units work together is becoming ever more complex. Yet the boom in LED technology is not alone in setting new operational and maintenance-related standards, since the highly diversified electronics sector is also making inroads on the field of street lighting, be it with management systems or electronic ballasts, sensor technology or databank applications. All of these things are set to increasingly change the work of street lighting managers, but these new applications naturally also open up new opportunities for lowering the workload involved in and thus the cost of providing street lighting. In all of this, the topic of cost-effectiveness must always be duly taken into account. But how can one keep abreast of the plethora of products on the market?

More than ever before, street lighting managers are called upon to keep informed so as to understand all the factors involved. In fact, doing so is vital if such managers are to remain capable of finding the most cost-effective solution for the future operation of a street lighting system.

This book intends to make a contribution towards satisfying this extended need for information, while also focusing attention on key factors. This technical manual on outdoor and street lighting deals with trending topics in the field of street lighting and is designed to be an everyday point of reference for users. Numerous specialists and authors have come together in this technical manual to give
you an overview of the latest knowledge and state of development with regard to much-discussed topics. These authors offer insight into a world that is characterised by a rapid succession of innovations – all of which need to be understood – and provide their expertise to give you, the reader, the tools to better understand this new wealth of information.

We, as the editors of this technical manual, owe these authors a huge vote of thanks for both their willingness to contribute and for accepting the enormous associated drain on their time. However, we would also like to thank the staff at the publishing company, without whose assistance it would not have been possible to produce this book.

*Birkenheide/Berlin, July 2015*

*Frank Bodenhaupt and Frank Lindemuth*
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Light is fundamentally important to us as human beings. Without sunlight life on earth would not have developed at all. Human beings process around 80% of information from their surroundings using their eyes [1].

Consequently, our very well being is dependent on light and good artificial lighting. While daylight is available free of charge and in abundance, we cannot reasonably have similar expectations for artificial lighting in terms of brightness levels to be achieved during darkness. Visible light makes up that small portion of the diverse spectrum of electromagnetic radiation (Figure 1) which the eye can see.

To be exact, the portion of electro-magnetic radiation between approx. 380 nm and 780 nm (1 nm = 10^{-9} m) is that which is perceived by the human eye as light or as brightness (Figure 2). This range differs from other electro-magnetic radiation only by virtue of the wavelength. Regardless of the frequency, the spreading speed of electro-magnetic waves in an empty space is approx. 300,000 km/s (speed of light). Light therefore spreads at a finite speed, but this is of little relevance for lighting engineering.
White light is made up of radiation of different visible wavelengths. The composition of white light can be made visible in the ensuing colour spectrum which is produced by directing a narrow beam of sunlight through a glass prism and projecting the exiting rays onto a board, reminiscent of a rainbow.

Particular regions of the visible spectrum are perceived by the human eye differently. The spectral sensitivity of human visual perception of brightness is internationally defined and termed the $V(\lambda)$ function (Figure 3). The physiology of the light-sensitive receptors in our retina allows us to see the world in bright colours. Under favourable conditions, a healthy eye can differentiate between around one million colours [2].

To technically describe a very specific colour impression, terms such as “grass green” or “sky blue” are of course insufficient. For this reason, a colour metric has been long since established to enable a technical characterisation. In this system all perceivable colours are arranged within a spatial structure, the so-called colour vector space.

Figure 4 shows a planar section through this colour space. We call this section a “colour chart”, or more precisely the “CIE 1931 color space chromaticity diagram” because this system of identifying colours is defined by that very CIE standard [3].
The location of a colour found on the colour chart is defined by its “chromaticity coordinates”. X and y coordinates are employed to specify this location on the colour chart.

**Luminous perceived colour**

To better describe the concept of light source colours imagine the following scenario: By slowly heating a metal, for example a lamp filament, we see that it begins to glow once a certain temperature is reached. The filament appears first as a reddish orange colour, as the wire continues to be heated, the colour of the light changes from a yellowy orange to white. If we increase the temperature above a certain point, the filament melts and the experiment is over.

The physicist Max Planck, performed a similar mental exercise in describing a theoretical radiator in mathematical terms, the so-called “black body radiator”. The colour on the theoretical filament that we would perceive as the filament gets hotter is shown by the curve drawn in Figure 4. This curve is called the Planckian locus in his honour. It establishes a correlation between the temperature and the light colour associated with it.

A colour of a light source in the colour chart lying on or close to the Planckian locus, can be thus identified not only by specifying the coordinates \((x, y)\), but also by indicating the temperature at the Planckian locus at this point. We call
this the correlated colour temperature, $T_n$, of the respective light source and it is stated in kelvins. This is today the recognized method of defining the colour of light sources.

**Figure 4**  Standard colour observer  
[Source: FGL Publ. 1]

**Table 1**  Division of the colours of artificial light sources according to correlated colour temperature

<table>
<thead>
<tr>
<th>Luminous perceived colour</th>
<th>Correlated colour temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Warm white (ww)</strong></td>
<td>below 3,300 K</td>
</tr>
<tr>
<td><strong>Neutral white (nw)</strong></td>
<td>between 3,300 K and 5,300 K</td>
</tr>
<tr>
<td><strong>Daylight white (tw)</strong></td>
<td>over 5,300 K</td>
</tr>
</tbody>
</table>
**Colour rendering**

Another important parameter in artificial light sources is colour rendering. This is understood as the propensity of a light source to allow illuminated objects to appear in “natural” colours. “Natural” colours here means the appearance of objects when these are illuminated using light sources familiar to us, for example, daylight or the light from an incandescent lamp (as far as this genus of lamp remains in use!).

The so-called colour test method has been established for the purpose of assessing colour rendering indices. Eight test colours have been defined and they observed under a particular reference light source and under the respective artificial light source to be identified. The resulting differences in the colour appearance of the test colours are evaluated in accordance with a fairly complex mathematical method.

The result of this method is a numerical value, the maximum of which can be 100. This numerical value is termed the general colour rendering index Ra. Whereas Ra = 100, in which case there are absolutely no colour deviations and colour rendering is optimal.

The lower the numerical value, the greater the deviations and the poorer the colour rendering of the respective light source.

**Luminous flux, light efficiency**

The human eye perceives visible radiation in accordance with the spectral luminous efficiency function for photopic vision shown in Figure 3 much more strongly in the middle of the visible spectrum than at the ends of the spectrum. The photometric unit, luminous flux, takes account of this.

*Figure 5*

Luminous flux

[Source: FGL Publ. No. 3]
Luminous flux, a photometric unit, takes account of this characteristic and is derived from the evaluation of the visible spectrum on the basis of the spectral luminous efficiency function for photopic vision. Luminous flux has the symbol $\Phi$. As Figure 5 shows, the luminous flux of a lamp radiates throughout the entirety of a space.

The luminous flux of a lamp is measured under defined photometric conditions and nominal luminous fluxes are defined internationally for many standard lamps. These are specified by the manufacturers in lamp catalogues.

The so-called light yield is the ratio of the luminous flux $\Phi$ of a lamp to the absorbed electrical power $P$ in lumens per watt [lm/W]. It is a measure of the efficiency of a light source. Incandescent lamps lay between 10 and 15 lm/W, high intensity discharge lamps can be up to 100 lm/W or more.

### Luminous intensity

Luminous intensity [$I$] in candelas [cd] of a light source (Figure 6) is the luminous flux radiated in a precisely defined direction. By measuring the luminous intensity of a light source in small angular steps in space, the Illuminance EV measured in lux is the ratio of the luminous flux $\Phi$ hitting a surface $A$ we obtain the luminous intensity distribution. This describes the various luminous intensities as a function of the angle of radiation and the surface itself (Figure 8).

For street lamps, this information is presented using the so-called C-coordinate system (Figure 7). Knowledge of the luminous intensity distribution of a light source is required for calculating the optimal lighting arrangement for a street.

$$ E = \frac{\Phi}{A} $$

---

*Figure 6*
Luminous intensity

[Source: FGL Publ. No. 3]
**Illuminance**

There is a correlation between the distance \( r \) between light source and the illuminated surface for greater distances known as the photometric inverse square law:

\[
E = \left(\frac{I}{r^2}\right) \times \cos \varepsilon
\]

*Figure 7  Relative light intensity distribution of a street lamp  [Source: Author]*

*Figure 8  Illuminance  [Source: FGL Publ. No. 3]*
The angle $\varepsilon$ is the angle of deviation of light incidence to the perpendicular with respect to the illuminated surface. This formula is employed to calculate the illuminance distribution in a street. Illuminance describes the quantity of lighting, but not the brightness of an illuminated surface. The perceived brightness of a road, for example, also depends on the reflectivity of the pavement used. A bright concrete pavement reflects significantly more light than a dark asphalt pavement.

**Luminance**

Luminance $L$ in candelas per square metre [cd/m²] describes the brightness of a luminous or illuminated surface. Luminance is the only photometric unit which we perceive as different levels of brightness on surfaces (Figure 9). Main roads are often planned on the basis of the average luminance of the driving surface. Average illuminance is used a quality criteria for all other roads.

![Figure 9](source:FGL Publ. No. 3)

**Literature**

[3] DIN 5033, Farbmessung
The Right Luminaires for Our Streets

Frank Bodenhaupt

Many people will only ever notice how important street lighting is when a technical problem cloaks a street in darkness. At all other times, street lighting is taken for granted, just like the presence of road signs and traffic lights. It is therefore hardly surprising that municipal street lighting has been treated and provided as an amenity of secondary importance by town and rural councils in Germany for decades, with only scant attention being paid or recognition being given to the work performed by street lighting managers. In many places, only very little or no money was invested into renewal and refurbishment. Throughout Germany, much of today’s street lighting is therefore outdated and now in need of modernisation. Numerous communities still operate luminaires that are significantly older than 40 years and, as a result, represent the state of the technological art as it was when they were installed. For most technical systems operated by town or rural councils, this would be unthinkable.

However, municipal street lighting was recognised as a possible area in which public spending cuts could be made at the latest when the regulations for implementing the eco-design directive governing lighting systems – ErP Directive for short – came into force. The fact that system components are extremely outdated has shifted the topic of street lighting into the focus of energy-saving concepts and refurbishment measures. This effect has been yet magnified by the federal government’s efforts to reduce CO₂ emissions, which have been driven by numerous attendant funding measures that also include attractive subsidies and favourable interest rates for refurbishment work carried out on street lighting. But the focus of these subsidies is solely on the possible energy savings to be made. Often enough, these potential energy savings are so tempting that either no or only too little attention is paid to the topic of cost-effectiveness when such deliberations are made.

But for operators of lighting systems who take a long-term view, saving energy cannot be the only factor to take into consideration; rather, account must be taken of the sum of all costs and savings. In fact, failing to take consideration of qualified cost-effectiveness calculations and merely focusing on energy savings during the decision-making process can become a false economy for town and rural councils over the long term. In this regard, a possible 30-year period of operation should be assumed, but at minimum the period of depreciation.

In the final analysis, the total costs seen over the entire period of operation are key as to whether or not a street lighting system will be cost-effective. The cost-effectiveness of a lighting system, in turn, is determined by countless operational, managerial and material-related factors. To list them all would go beyond the scope of this article, but their sheer number also shows that professional management of street lighting systems entails more than just, simply put, switching the system on and off, but much rather belongs in the hands of experienced professionals.
At the same time, modern technologies are on the rise that will go to decisively change the face of street lighting in the coming years. Above all, LED technology is set to open up far-reaching options for saving energy, maintenance and operating costs – with a simultaneous increase in comfort and convenience – for street lighting in the future. What is more, the options available for controlling the operating data of street lighting are also increasing, predicating a shift towards lighting systems that can respond to actual lighting needs. A key element of a cost-effective lighting system is ensuring diligent material selection and, in this context, particularly the right choice of luminaires.

As street luminaires must be understood as long-term assets, getting this selection process right is of particular importance. The quality of any given luminaire plays a very major role, especially considering service lives of 30 years and more.

**Types of Luminaire**

Municipal street lighting presents itself in many forms within an urban landscape. The most widespread of these are street luminaires whose rather technical character solely serves the purpose of illuminating streets and which were specifically constructed to this end. These luminaires shape the look of main roads and high-traffic housing development areas. But luminaires of this kind can also be found in less well frequented streets, right up to residential roads. The design and look of such luminaires, even if made by different manufacturers, varies only little since function and usability will have been the main design focus, which often leads to very similar looking results. The outer appearance of these luminaires will generally have been kept intentionally timeless and unspectacular. The difference between the individual brands can be found in the hidden details so that when it comes to selection and evaluation, the opinion of an expert is called for – an expert who will usually prefer the technical advantages of this luminaire type.

*Figure 1*

*Typical technical street luminaire*
In contrast, street luminaires destined for urban areas that are well frequented by pedestrians, such as inner cities and residential areas, are often chosen with an eye to decorative features. In these cases, street luminaires are not only expected to illuminate the streetscape, but also to become an integral part of the urban furniture. Furthermore, the radiated light is meant to create a pleasant ambience and present the urban space in the best light – even at night. A broader type of light beam is generally preferred in such cases, which also inevitably changes the look of both the luminaire poles and the luminaires.

Whereas higher light points tend to be preferred for illuminating main roads, lower light points are usually chosen for the above-mentioned residential and inner city areas, which naturally go hand in hand with different lighting technology. The design and appearance of the final light fixture thus becomes a key criterion when choosing the right luminaire. Within the context of other street furniture such as benches or bollards, design aspects take centre stage, in which regard countless options are at the disposal of designers as well as light and space planners to make lighting an integral part of effectively showcasing the urban landscape at night. Modern light sources and numerous light-guidance options make it possible to provide state-of-the-art and cost-effective street lighting with decorative street luminaires.

But even for decorative luminaire types, the quality of the technology, materials and components is decisive if the provided street lighting is to be both cost-effective and ensure a long service life. However, due to the numerous tasks that need to be performed by municipal street lighting, there is not just a need for decorative and technical luminaires, but equally for luminaires that are solely designed and used for special applications, which include spotlights and lighting for underpasses and tunnels.
Still, despite the large number of luminaire types that can be found in municipal operation, the majority falls into either the decorative or technical street luminaire category. Ultimately, all luminaires should satisfy the same quality requirements as apply for standard luminaires used in street lighting.

Due to the enormous technical diversity of modern street luminaires, many users find it difficult, if not impossible, to tell if the quality of a luminaire is good at first glance. Nonetheless, there are a number of characteristics that indicate whether a manufacturer is retailing a product that has been developed and produced with the necessary diligence and that satisfies current technical standards and directives.

**Labelling**

Luminaires must be labelled with all mandatory test marks, which can be found on the luminaire label. Mostly this will be attached to the inside of the luminaire in an easily visible spot. This label must be permanently bonded to the product and be impossible to remove without considerable effort.
In this context, the CE and the WEEE marks are worthy of particular mention. By attaching the CE mark, a manufacturer declares that the product satisfies all relevant EU Directives, especially the Low-Voltage and EMC Directives. (Also see the report on EMC testing in this book.) The CE mark is not based on testing by an independent testing institute; responsibility for attaching it rests solely with the respective manufacturer. Furthermore, luminaires that entered the marketplace after 13 August 2005 must bear a symbol indicating the need for separate disposal of electrical and electronic equipment in accordance with the labelling provisions of the WEEE Directive. The symbol depicts a wheelie bin with a line drawn through it. At the same time, the manufacturer of the product must be clearly identifiable.

By affixing an ENEC or VDE sign, the manufacturer can further document that a certified testing institute was called upon to provide neutral confirmation that the respective luminaire satisfies all safety-relevant provisions. The user can thus rest assured that the product conforms to the current state of the technological art. In contrast to the CE mark, the ENEC or VDE sign can be seen as a mark of quality.

Having tests conducted by independent testing laboratories, and in particular the complex and extensive testing to which a luminaire has to be subjected in order to attain ENEC certification, is work-, time- and cost-intensive for the respective manufacturer. Furthermore, to ensure a luminaire does not lose its ENEC sign, each and every change made to it will require the luminaire to be retested if it is
to retain the right to display its ENEC sign. Given the fast pace of change that characterises the LED market, which is generating new LED developments in increasingly rapid succession, it is certainly understandable that luminaire manufacturers are tending towards not applying for ENEC recertification every time a change is made to an LED luminaire. The attendant costs would simply be too high and would ultimately have to be borne by the customer. Since manufacturers are not obliged to attach an ENEC sign to products, end customers have little choice but to rely on the experience of and statements made by the provider and/or their own expert knowledge.

**Luminaire Quality**

Determining the quality of a product is not just a matter of reading up on certain product properties, but should also take further points into account:

- **Qualified pre-sales support and advice** offered either by the manufacturer or the provider. This includes expert information, advice concerning the correct installation site, cost-effectiveness considerations, training and planning assistance. But clearly structured and informative product documentation equally forms part of good customer service.
- **Qualified after-sales advice**, installation and commissioning advice as well as fast response in the event of warranty claims. Guaranteed supply of spare parts for many years or, better still, even decades into the future is another sign of high product quality. Nothing would be worse than having to exchange all luminaires in a system prior to the end of their usual service life simply because a spare part was no longer available. Unfortunately, this is a likely scenario with some of the lighting products currently retailed on the market.

In order to minimise energy and maintenance costs as far as possible, particular importance should be attached to the photometric and technological quality of a luminaire. And producing a luminaire with a similarly high-quality design is no longer an impossibility given the products available on today’s market.

Luminaires of superior photometric quality are perfectly aligned with regard to their reflector and lamp technology. In this context, the following criteria should, as far as possible, be fulfilled:

- The respective lighting technology should permit a large distance between light points (luminaires) while still ensuring a standard-compliant level of illumination, which in turn serves to reduce power and maintenance costs. Standard-compliant also means that mandatory criteria such as glare and ambient brightness are met.
- The generated light is mainly directed onto the effective area. In the context of street lighting, the term “effective area” naturally not only applies to the street or road itself, but equally to adjoining areas such as pavements or cycle paths. Optimised light guidance minimises the necessary energy input.
Luminaires should be designed for operation with one of the following light sources:
- LEDs
- halogen metal halide lamps
- high-pressure sodium discharge lamps
- compact fluorescent lamps

Depending on the specific application, each of these light sources has its own special advantages, but all of them are suitable for creating cost-efficient lighting systems.

High-pressure mercury vapour lamps as well as incandescent lamps should be avoided since they are inefficient and spare parts supply cannot be guaranteed in the years to come or, as in the case of high-pressure mercury vapour lamps, is impossible within the EU.

Whereas a luminaire of high photometric quality mainly results in a reduction of energy costs, one of high technological quality will tend to minimise maintenance and installation costs. The following points should be ensured by future users when choosing a luminaire:

- At minimum, the luminaire should feature an IP54 degree of protection. Most luminaire manufacturers are capable of offering products suitable for systems requiring an IP65 degree of protection or higher. A high degree of protection also ensures optimum protection for reflector technology and electrical componentry, which again lowers cleaning and maintenance costs. A high degree of protection is a must when it comes to LED luminaires if the high-quality components are to be given optimum protection. Luminaires with a high degree of protection must be fitted with a pressure-compensation valve to prevent the formation of condensation, which would permanently damage the system. In this regard, an exchangeable valve membrane is key to avoid clogging with dust and other airborne pollutants, which would render the valve ineffective and let condensation form inside the luminaire.
- Protection class II luminaires should be given preference.
- The technology should provide suitable options to reduce the luminaire’s power uptake; this can be achieved with a one-step reduction, multi-step reduction or electronically via a dimming function.
- Easily exchangeable cover and luminaire casing seals are another advantage since this helps to keep luminaires properly sealed over many years.
- Luminaires should be resistant against environmental factors such as vandalism, but also hail, for which reason the cover material must be impact-resistant. Rounded covers and flat, toughened glass are more resistant than covers with sharp corners.
- The manufacturer of the selected luminaire must provide an extensive range of installation accessories and spare parts over a longer period of time. This is mostly the case for luminaires of a more timeless design that will remain part of the manufacturer's range over the longer term.
With the exception of LED luminaires, street luminaires must be able to be opened without requiring tools as this also serves to save maintenance time and thus costs. Electrical components should be fitted with plug-in connectors that are easy to release for removing the terminal block.

Care must be taken to ensure that the cover features a water drainage edge to protect it from dripping water and soiling.
Care must be taken to avoid luminaires of excessive weight. Standard luminaires should not weigh more than 15 kg. Luminaires of higher weight are difficult to mount and usually require two installation technicians. In addition, heavy luminaires can impair the structural stability of luminaire poles, many of which will not have been designed to cope with heavyweight luminaires. Due to their solid heat sinks, the high weight of recently developed LED luminaires means that attaching two luminaires to one pole will often overload the existing equipment.

If consideration is taken of all the criteria that go to make up a high-quality luminaire, it is easy to understand that many of these points can only be ensured with experience and expertise in the field of luminaire production. And since such high-quality products are also expected to come with an extended service life, it is equally essential to ensure that spare parts supply can be guaranteed over many years to come. The fact that developing and implementing the above-named quality criteria will also affect the price is therefore logical. But the financial advantages that can be achieved with high-quality luminaires in terms of reducing energy consumption and lowering maintenance and upkeep costs are far greater than the higher initial investment needed to purchase the product. In contrast, low-cost luminaires are usually more expensive in the long run.

But making the topic of energy efficiency the sole focus of attention, as currently tends to be the case, comes with a particular risk of ignoring the topic of cost-effectiveness in favour of promised energy savings. The wish and often also the political and public pressure to make rapid and significant energy savings prove to be too great. Yet street lighting should continue to be a long-term asset in the future as well. As a consequence, high-quality products are therefore key to a cost-effective street lighting system.
Urban space / system / LED luminaire

Systems as a guiding principle when selecting luminaire types and special aspects of these in the LED age

Peter Uhrig

Figure 1  The importance of the fixture design vary according to the dimension of the installation

Current developments in LED technology are leading to dynamic changes in the design of exterior luminaires and how they function. During the fevered years of their launch onto the market, subjects such as technical feasibility, lighting current levels and efficiency were in the spotlight but as LED technology has become more established, the focus has returned to important issues like visual comfort and the question of what the best luminaire is for a particular public space.

There are many reasons and methods for deciding which solution should be used in the course of the planning process. Yet despite the wide range of options, parameters of a general nature do exist when planning public spaces. In selecting and arranging luminaires, it is always important to consider proportionality between urban space, system structure and luminaire.

LED technology and its light properties have resulted in new possibilities and conditions in this context. As well as the provision of horizontal illumination for requirements in standards and directives, the vertical peripherals also need to be taken into account. Whereas in the past it was taken for granted that facades or similar areas were also illuminated due to the unavoidably scattered light of conventional lighting technology, such space-defining areas are now threatening to sink into darkness due to LED light being directed with precision onto horizontal roadways.
The technology shift and new possibilities

LEDs make available a light source that is different to the lamp technologies we were traditionally familiar with, not only in respect to efficiency and service life but also in terms of size and directional characteristics. Following the launch of LED technology onto the street lighting market, the focus lay above all on energy issues. The new complexity of performance characteristics and a lack of uniform methods for comparison consolidated this limited viewpoint even further.

However, as practical experience of LEDs has grown, the perspective has shifted to quality of light, the design of luminaires and their spatial effects. The challenge now is to recognise the potential and possibilities offered by the latest LED technology and to make good use of this.

Generally speaking, a balanced view of technical and planning requirements is required regardless of the technology used. This is the result both of simplifying the analysis models required to quantify lighting on the one hand and individual planning for the specific space on the other. Consequently individual strands of planning may appear to be weighted differently in generally quantitative solution approaches as opposed to specific design approaches.

Luminaires for inner-city areas

Selection of fixtures for public lighting must always take place in close coordination with the existing environment. This particularly applies in inner-city areas where large numbers of people tend to linger for longer periods as pedestrians compared to purely traffic-oriented streets. In addition to the large number of influencing factors that need to be taken into account, the type of use must also be brought to the foreground. It is however also important to take into account the architectural character of the urban space and especially the distinguishing features of existing fittings. For this, it is essential to look closely at the location’s individual evolution in terms of its urban development and history.

Dimensions of urban spaces, lighting systems and luminaires

Proportionality between urban space, system geometry and lighting fixtures forms the link between technology, design requirements and characteristic existing reference points. Of course, the selection of a type of luminaire is not defined by proportions alone. Other requirements are often simpler to incorporate if a basic structure exists that is predefined by dimensions and proportion. This is particularly the case in developed inner-city areas.
Depending on the size of the space and on lighting engineering requirements, a light fixture’s design along with the resultant mounting heights, pole distances and the positions of the light heads on the poles will vary in importance.

Large-sized systems

Large spaces, which frequently accommodate an important traffic infrastructure (such as crossroads, bridge approach roads or connections to public transport), require high levels of illumination. At the same time illumination often needs to be generated from just a few pole locations. This frequently requires multiple arrangements of high-power luminaires on one pole with very high mounting levels. These luminaire clusters are located so far away from the field of vision and direct perception of human beings that it is impossible for this single luminaire to directly influence the appearance of the space. The pole itself is reduced to a mere static carrier and is therefore perceived, at best, as part of a technical infrastructure.
Larger and medium-sized systems for the lighting of main roads and trunk roads

Urban development dimensions of inner-city roads can mostly be classified unambiguously due to the surrounding historical architecture that has developed over time. This surrounding perimeter construction defines the proportionality between road width, roof height and the empty space in between that is important for perception.

Figure 4 System structure with a distinctly neutral appearance

Roads within a highly developed urban context such as this, that are important for traffic, require systems that do justice to heightened lighting requirements. This results in mounting heights that are just about (if at all) within the perception range of a person moving within the space. The light fixture itself will only gain any sort of significance if the proportions of pole, arm and the luminaire mounting/connection are sufficiently well-balanced. As a result, (depending on the quality of the overall design of luminaire, pole and connection), systems with a distinctly neutral appearance and systems that function as urban design elements are both possible.

Using typical proportions for main roads and trunk roads, the system comprising pole, luminaire and connection can become the distinguishing and identity-sustaining element within the urban space. Prior to planning, it is essential that an analysis of the surroundings is made and a clearly defined objective is set. The results will inform as to whether the effects attained will endure for the long term or prove merely to be a fashionable short-term design trend. In most cases, it is systems with poles and arms that are expressive enough to have a defining effect on the space.
Upswept poles – a special case

Systems with upswept poles are a particular artefact from the heyday of fluorescent lighting technology as used in street lighting during the 1960s and they constitute a special case with regard to system proportionality. Their expressive, curved shape is capable of providing a visual parenthesis for urban space perspectives without the built-up space actually defining a certain volume. Upswept poles are a good example of how differently the individual components of the overall specification can mould a system. Rather than the luminaire head, it is the bearing structure that dominates the perception of the luminaire. There is currently a huge demand for upgrades to systems with upswept poles which means that this type of luminaire needs to be considered in detail.
Pole-top luminaires in historical town centres and residential areas

From the above statements about large and medium-sized luminaires it will be evident that, as the light point height decreases, the luminaire heads move further into the user’s field of perception and their influence on the design of the urban environment increases. Because of this, pole-top luminaire fixtures, with their comparatively low mounting height, are presently attracting much attention.

This phenomenon, which is brought about by the user’s physical proximity to the luminaire, is further backed up by its symbolic function in design theory: the pole-top luminaire can be interpreted as a continuation of the flaming torch, which is firmly established as an archetype in human history. In both cases, a vertical luminous element is mounted centrally on a linear carrier.

Pole-top luminaires with conventional lamp technology generally result in a construction whereby an optics system and the design-defining luminaire body are grouped concentrically around the lamp housing. The design language of this fixture typically makes use of simple geometric shapes. In turn the proportion of the luminaire to the surrounding environment is the key to its harmonious appearance in the urban design context.

Figure 7  Pole-top luminaires

New possibilities and conditions due to LED technology

Use of LEDs is now opening up entirely new possibilities with respect to the structure and shape of luminaires. The light source need no longer be placed at the fixture’s central axis to achieve a convincing lighting engineering result. Technical issues, such as the thermal connection of the LED light source to the housing body, are leading to solutions that are no longer congruent with the
archetypical image of the flaming torch. Of course, this extended range of multiform shapes still needs to be used in accordance with the standards of design theory if it is to meet the heightened requirements of fixtures in systems in historical town centres and residential areas.

![Figure 8](image.png)

**Significance of the perpendicular for urban space perceptions**

Persons can only perceive spaces if their vertical peripherals can be experienced. As well as providing sufficient lighting to horizontal areas for visibility in traffic, planning in urban spaces also needs to be committed to the perpendicular. With conventional lighting technology, sufficient scattered light is for the most part available on vertical surfaces. The deflected, direct light component of lamps illuminates adjacent facades almost by accident. In the worst case, this will be so intense that it causes disruptive light and dazzling in residential buildings.

**Optics systems for targeted light direction**

Light radiated by the LED point light source can be guided considerably more precisely with optics systems than with conventional ellipsoid or clear-tube lamps.

This highly-efficient light direction is virtually devoid of scattered light. The effects of this vary depending on the system geometry. With higher-placed systems, extremely high luminous intensities on windows of residents situated behind luminaires with unobstructed high-pressure discharge lamps can be considerably restricted due to use of LED technology, however facades appear much too dark when pole-top luminaires are only upgraded taking road traffic aspects into account. In order to illuminate a street with houses so that it remains recognisable, facades need to be illuminated as far up as approximately the second sto-
rey. If low light point heights are used with pole-top luminaires and distribution is directed downwards only, the urban space will not be sufficiently distinguishable from the blackness of the night sky.

![Figure 9 Dark facades/distinguishable facades](image)

### Dazzle perception

LED luminaires are often described as dazzling. Public discussion focuses here on the reduced size of the light emitting surface of the LED itself and on the very precisely directed, closely concentrated light. However our current knowledge tells us there are no objectively measurable values that provide evidence of this sort of dazzling from normal vantage points at usual eye level. Rather, the LED luminaires, (which are to some extent still perceived as new or at least not old-fashioned), appear to be leading people to lift their heads up and stare directly into the small optics units, thus resulting in dazzling. This is in turn being generalised as an objective perception. However, research on the dazzling of LED luminaires is still in its infancy. For the design of luminaires, we can conclude today that observation of objective, tried-and-tested design standards contributes to the acceptance of modified LED lighting technology. Poor design will at the very least increase their value as an attraction, thereby leading to the sort of LED light gazing described above.

### Summary

Following a phase where the focus was primarily on the technical parameters of LED light solutions for street lighting, aspects of urban development and design will need to be looked at more intensively in future. For the planning of lighting for central inner-city areas, observation of dimensionality serves as the basis for selecting the correct luminaire. At the same time, the lower the light spot height, the more important the design quality of the luminaire itself will be. In addition, attention needs to be paid to a balanced proportion between all sizes i.e. that of the space, the pole, the connection or mounting for the luminaire and the luminaire itself.
LED technology has opened up new design scope, particularly for the shape of luminaires. However these new-found freedoms must also be understood as a challenge. For smaller dimensions in particular, the optics systems of LED luminaires must provide a sufficient light proportion to illuminate vertical surfaces of urban spaces e.g. the facades. In the street lighting of the future, this aspect needs to be especially emphasised with respect to standardised energy assessment criteria. In addition only a premium-quality approach to the design of the luminaires themselves can guarantee sojourn quality and a sense of well-being, resulting in an urban space that is positively perceived, particularly in regard to dazzle.
CE Marks don’t always mean what you think they mean

Along with product safety, electromagnetic compatibility (EMC) is one of the greatest challenges to lighting design and performance. Up to now, the ability of a product to perform within EMC limits was largely dependent on ballasts and the quality of their integration in the luminaires. In contrast to conventional lighting, however, LED lighting products have a second electronic component that requires careful scrutiny. This is yet another reason why operators should ask when buying lighting products about product EMC test standard compliance.

EU laws and regulations require for the sake of consumer and operator protection that certain types of products, including lighting, may be made available for sale only if they are compliant with specific safety and health standards. The CE Mark is a declaration of conformity verifying that products conform to all relevant EU directives. It is not issued by an institute, but rather affixed by the manufacturer to the product. The manufacturer is solely responsible for the product’s compliance with EU requirements. For street lights, these requirements include EMC standards.

In Germany, the Bundesnetzagentur (Federal Network Agency), which is entrusted with the monitoring and testing of compliance for the CE Mark and the EMC Directive, found over a quarter of 1,113 streetlights it tested in 2010 were non-compliant.

EMC testing of individual components does not add up to system compliance

VDE, Germany’s Association for Electrical, Electronic & Information Technologies, defines EMC as “the ability of an electrical or electronic device to function in its electromagnetic environment satisfactorily without significantly disturbing the environment, to which other devices also belong.”

Expected of lighting products is that they are sufficiently resistant to interference and emit acceptably minimum electromagnetic energy. Testing the individual components, such as control gear and LED modules, for compliance is not sufficient. The complete lighting system must comply with the EMC requirements. The following EN 61000-4-3 criteria are used to determine immunity to external electromagnetic disturbances (Figure 1):
Police radios or mobile phones emit electromagnetic energy that can interfere with the operation of streetlights. The tests for immunity determine if the lighting functions without interruption, which would appear as flicker and fluctuating or even the absence of luminous output. EMC tests to determine whether streetlights emit electromagnetic energy employ the following parameters (Figure 2):

- interference field strength 30 MHz to 1 GHz (as per EN 55011) (susceptible to disturbance are mobile phone reception and transmission, and police radio transmission)
- disturbance voltage 9 kHz to 30 MHz (as per EN 55015) (susceptible to disturbance are devices that are connected to the same power supply)
- power supply disturbance (harmonic EN 61000-3-2 and flicker EN 61000-3-3)
LED streetlights are subject to the same EMC tests as lighting that is configured with conventional lamps, however, due to the greater proximity of electronic components, it is usually more difficult for LED lighting to meet EMC standards.

**Protection**

If a lighting product exceeds EMC limits in the course of a test, the manufacturer has the obligation to implement suitable measures that will ensure the product will comply with EMC standards. Improvements to products that are already ready for the market are expensive for manufacturers and cost them very valuable time. For this reason, it is advisable that manufacturers perform EMC tests on products while they’re in development. Integration of EMI filters, ferrites, capacitors and inductors is possible while products are in development. To protect luminaires from voltage surges that may occur in the power supply lines with the turning on or off of machines, systems may incorporate metal-oxide varistors and gas discharge tubes. Both discharge surges to the ground or via power line. If such design features are not present, surges may damage control gear or LED modules irreparably, leading to the total loss of the

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**Figure 2**
The EMC Directive also requires streetlights to comply with disturbance emission limits.
luminaire. Besides ballasts and LED modules, power leads are also key factors in a lighting product’s EMC. Very important here is that the primary and secondary wiring, i.e. control gear in- and outputs do not cross.

To have certainty that a LED streetlight meets EMC standards, buyers and operators should request manufacturers to provide a suitable declaration of conformity, preferably one issued by a certified EMC testing institute.
The old Hanseatic city of Lemgo is well-known for its historic city centre, its OWL university, East Westphalian/Lippisch specialities, a successful handball team and a good deal more. It has recently been the benefactor of highly up-to-date lighting. Lemgo, idyllically set in the district of Lippe, was one of the first councils in the region to take the theme of LED lighting to heart and consistently implement it. Modern LED luminaires replaced obsolete liked heads with high pressure mercury vapour lamps.

Today around 2,800 LED luminaires from Siteco illuminate the town with a population of 40,000. This is approximately 60 % of all light heads in the urban area. Modern LED technology contributes to the extensive climate protection concept that the city has drawn up.

The balance of the refurbishment project: Lemgo saves around 60 % of energy, costs and carbon dioxide compared to consumption values before refurbishment. Specifically, this is around 550,000 kW/h of electricity annually, corresponding to a quantity of approx. 6,000 tonnes of damaging CO₂ greenhouse gas. The city also spends around 90,000 euros less each year for energy consumption of its lighting installation due to the refurbishment with modern LED luminaires. Cost reductions due to lower maintenance levels and lamp replacement costs (not applicable with long-life LED technology) are not included in this calculation.
In the past, light on the streets of Lemgo came from inefficient high-pressure mercury vapour lamps with inherent heavy metal loads. “Most of the luminaires would have to have been replaced anyway because of their age. And there were also no retrofit solutions for the luminaires already installed,” explained Fritz Meise, who initiated and supervised the project in the Lemgo building authority offices. “No more HQL lamps will be available to purchase in 2015 anyway. That was also something we considered.” Fundamentally decisive was the subsidy program of the Federal Ministry for the Environment 2011/2012. “We never would have achieved the specifications with SON lamps. With the planned LEDs solutions though, we received the complete 40% subsidy quota.”

In the meantime, Meise has transferred the LED lighting project in Lemgo over to his successor, Dietmar Fillies. Both agree that “At some time you simply have to decide to jump on the bandwagon.” Christian Bintz has the same view, who works for the Lemgo city authorities who implemented the lighting as a service provider and partner. “The Department of Works are always interested in new and future-fit technology,” he explained, also referring to the Lemgo energy sup-
ply. The energy mix of the Hanseatic city consists of up to 70 % of self-produced thermal power. “We’ve updated around 60 % of our lighting systems to LED, which was definitely the right thing to do.” Mr Bintz is sure that this lighting technology belongs to the future in Lemgo.

Previous doubts certainly existed: “Of course we considered whether the wide use of LED technology wasn’t perhaps premature,” remembers Fritz Meise. They also considered stability of the electronics, the theme of glare, and also the level of acceptance with city residents. Fritz Meise and his team analysed the topics in detail and assessed and compared manufacturers and tenders. “We looked closely at suppliers where we’ve had good previous experiences with. And we mainly wanted a partner who was there in the future for us as well.”

The result: Siteco Streetlight 10 mini luminaires for technical road lighting at 12, 8 and 5 metres for main roads and collection roads, and modern LED mushroom luminaires for residential streets and areas.

Particular attention was paid to installing just a few different types. “We installed Streetlight 10 so that we make do with two different light output levels,” explained Dietmar Fillies. The advantages: stock keeping, logistics and purchasing. The lighting installation also has a uniform appearance, and Streetlight 10 as a technical road luminaire simply looks very good.”

Lemgo concentrated on the essentials for its refurbishment of road lighting, and also consistently implemented its plan of replacing HQL luminaires to give visible and tangible results. “Upgrading 2800 light points in just nine months seemed utopian in the beginning,” said Meise and Fillies about their initial doubts. “But everything was done with a high level of precision,” complimented the specialists with regard to the services of the luminaire suppliers.

The project continues to be supervised by the exterior luminaire expert Barbara Gembus who accompanied the project on the Siteco side from the beginning and was available as a contact person during the complete project duration. And afterwards as well of course, because following the upgrading of technical road lighting in Lemgo, focus is now being turned to lighting for the historic city centre.
Degradation of white high power LEDs: causes and behavior

Tran Quoc Khanh

1 Construction of the modern white High-power-LEDs

The construction principles of the modern white High-power-LEDs are different from company to company. Generally, a white LED consists of the following components:

- A blue chip with a peak wavelength in the range between 440 nm and 465 nm. This blue chip emits the blue optical radiation with a bandwidth of about 25–30 nm.
- A phosphor mixture: the phosphor particles partly absorb the blue radiation which is converted partly into the thermal energy (heat energy) and partly into radiation with longer wavelengths (yellow, green or red phosphors). The phosphor particles are mixed with an optical silicone so that the whole mixture can be brought according an accurate technological process on the surface of the blue LED-chip as dome or as a thin plate.
- The substrate of the blue chip is mounted by soldering or adhesive methods on the submount which is then mounted on a carrier material in order to achieve a mechanical stability and to transfer the thermal energy from the LED over the carrier to the following cooling systems like aluminum systems.
Wire contacts connect the anode and cathode of the LED-chip into the pads to which the current can be directed from the driving LED-electronics.

A primary optics has the task to direct the radiation from the LED-phosphor-system upwards to the ambient field.

Because the thermal conductivity of the phosphor mixture and of the primary optics is relatively low, the dominant part of the thermal conduction is rather realized by energy transfer from the silicone-phosphor-layer through the junction-layer of the LED-chip and submount to the carrier, before this thermal energy can be distributed to the electronic board and cooling systems.

2 Most sources of LED-degradation

The behavior of LED degradation can be grouped into following issues:

- **Depreciation of the photometric quantities:** from all photometric quantities, the luminous flux depreciation is the most used parameter. However, from the view of lighting designers and luminaire users, the change of the absolute luminous intensity (I in cd/m²) and its distribution over all emission directions is much more important.

- **Change of color characteristics of the emitted LED radiation:** for most users and luminaire designers of indoor lighting the color shift is a key criterion for evaluating the acceptance and usability of the LED products (e.g. museum and shop lighting, stage and film productions, hotel and office lighting). For street lighting, this issue is not of essential importance.

- **Change of the electrical and thermal characteristics of the LED component:** at a constant LED current, the change of the forward voltage is an indication for the change of the electrical resistance of LED chip and/or packaging (contact place between bond wires and chip, change inside the pn-depletion layer, substrates and in the adhesive layer between substrate and electronic boards).

In the time range between 2011 and 2014, a research project with 5 German research laboratories was performed in order to define a draft for a LED-product quality label (PQL). In this frame, aging tests with many hundreds high and medium power LEDs have been conducted. In this chapter different degradation mechanisms will briefly be presented before going to the detailed description of the aging behavior of high-power LEDs aged 7,000 hours in the test room of the Technical University Darmstadt (Germany).

Figure 2 shows the cross section of a modern high-power LED with transparent primary optics and the phosphor plate on the LED die (see [1]). The LED-chip is connected with a ceramic substrate for mechanical stability and heat spreading aims. The underlying side of the ceramic substrate is soldered on a printed circuit board (PCB). From Figure 2 it is visible, that damages can take place between the packaging and the chip. The dark areas at the left and right sides
of the chip obviously show the places of ionic contaminations. These effects are an indication of the leakage in the LED housing or during the packaging process which also damages the phosphor layer at the center of the chip (see [1]).

![Figure 2](structure-of-a-modern-high-power-led.png)

**Figure 2** Structure of a modern high-power LED  
[Source: University of Applied Science, Hannover/Germany]

From the packaging aspects, several defect causes can be described as follows (see [1,2]):

- Contact problem of the bond contact (ball form), delamination of the die attach, delamination of phosphorus layer.
- Contact problem between the transparent lens and the bond wire which have different thermal expansion coefficient so that at a high temperature change (temperature shock) the bond wire can be disconnected from the bond contact or broken.
- In the most SMD-LEDs, the primary optics is silicone lens and can therefore transport the humidity.
- In a white LED, blue light source emits short wavelength radiation with relative high photon energy which can cause an yellowness of the primary optics and silicone encapsulate.
- The silicone encapsulate material and the silicone lens consist of silicone polymers and are reactive to a number of chemical substances and gases (see [3]) which can be found in the surrounding air (e.g. as street lighting in an industrial area or in a megacity with a high density of traffic and industrial use) or in the materials used (O-ring, glues, conformal coating) for the luminaire housing and for electrical cables. The consequence of these reactions is the yellowness and darkening of the LED structure. In Figure 3, the darkening area at the center of a studied LED is the outcome of the existence of PVC-cables inside the luminaire unit.
The base of the test methodology in the test lab of the TU Darmstadt is the American standard IES LM-80-08 with the following test and measuring conditions which are described in Table 1:

<table>
<thead>
<tr>
<th>Requirements</th>
<th>LM-80</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Case temperature with 2 °C uncertainty, monitored during the life testing</strong></td>
<td>55 °C, 85 °C and at a higher selectable temperature</td>
</tr>
<tr>
<td><strong>Temperature of the surrounding air</strong></td>
<td>Within –5 °C of the case temperature during testing</td>
</tr>
<tr>
<td><strong>Humidity</strong></td>
<td>Less than 65 RH throughout the life test</td>
</tr>
<tr>
<td><strong>Airflow</strong></td>
<td>To be minimized</td>
</tr>
<tr>
<td><strong>Operating orientation</strong></td>
<td>The convection is made possible</td>
</tr>
<tr>
<td><strong>Input voltage</strong></td>
<td>Ripple voltage shall not exceed 2% of the dc output voltage</td>
</tr>
<tr>
<td><strong>Line voltage wave shape</strong></td>
<td>The total harmonic distortion not exceed 3% of the fundamental</td>
</tr>
<tr>
<td><strong>Input current regulation</strong></td>
<td>Input current monitored and regulated within ±3% of the rated rms value during life testing and to ±0.5% during photometric measurements</td>
</tr>
<tr>
<td><strong>Case temperature</strong></td>
<td>Thermocouple measurement system monitoring the case temperature at the manufacturer-designated case temperature measurement point</td>
</tr>
<tr>
<td><strong>Elapsed time determination</strong></td>
<td>To be measured via video monitoring, current monitoring with an uncertainty within ±0.5%</td>
</tr>
<tr>
<td><strong>Recording failure</strong></td>
<td>Checking for LED light source failures either by visual observation or automatic monitoring</td>
</tr>
<tr>
<td><strong>Forward voltage monitoring or measurement</strong></td>
<td>Not required</td>
</tr>
<tr>
<td><strong>Measurement</strong></td>
<td>Total spectral radiant flux measurement is recommended for determination of luminous flux and chromaticity</td>
</tr>
</tbody>
</table>

Table 1  The test and measurement conditions for LED lifetime analysis according LM-80 (see [4])
In the research project two types of high-power white LEDs with a color temperature of 4,000 K from two different well-known LED-manufacturers have been aged and characterized. Table 2 represents the specifications for the study:

<table>
<thead>
<tr>
<th>Issues</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of the LEDs for each working point</td>
<td>20 sample</td>
</tr>
<tr>
<td>Case temperature</td>
<td>55°C, 85°C and 95°C</td>
</tr>
<tr>
<td>Current</td>
<td>350 mA, 700 mA and 1,000 mA</td>
</tr>
<tr>
<td>Measurement conditions</td>
<td>( T_c = 25°C, t = 20 \text{ ms} )</td>
</tr>
<tr>
<td>Time interval</td>
<td>Every 1,000 hours</td>
</tr>
<tr>
<td>Measured quantities</td>
<td>( I-V )-diagrams, spectral radiant flux, luminous flux, color coordinates, ( CCT ), thermal resistance</td>
</tr>
</tbody>
</table>

**Table 2**  Test and measurement specifications at the aging laboratory of the Technical University Darmstadt

![Test room for LED aging at the TU Darmstadt](image-url)
3 Change of the electrical behavior

At constant current conditions the aged LEDs were periodically measured on the forward voltage. The results are illustrated for the LED 1-type in Figure 5 and for the LED 2-type in Figure 6:

**Figure 5**  Change of the forward voltage of the LED 1-type with the averaged value and standard deviation among the 20 examples for each aging condition

**Figure 6**  Change of the forward voltage of the LED 2-type with averaged value and standard deviation among the 20 examples for each aging condition
From practical user-view, the following conclusions can be made:

- For some conditions like 1,000 mA and 95°C, the voltage of the LEDs of the type 1 increases at constant current bringing more electrical power compared to the electrical power of the LEDs at the beginning of applications.

- The voltage of the LEDs of the type 2 decreases about 8–10% after 7,000 hours aging time. If the current is constant, that means a reduction of the electrical power relating with a reduction of the LED luminous flux. From lighting designer’s view and user’s view, a lighting plan at the beginning for a certain street cannot be fulfilled even after 7,000 hours because the luminous flux is remarkably reduced.

Figure 7  Luminous flux degradation of the LED 1-type at 85°C

4 Change of the luminous flux-lumen maintenance

The aging data for the LED 1-type for condition $T_s = 85°C$ and for three currents 350 mA, 700 mA and 1,000 mA are shown in Figure 7. For this LED-type and for used aging conditions the degradation rate is moderate. In Figure 8, the aging data on luminous flux for the LED 2-type under the same aging conditions are illustrated.

Only the aging condition with 350 mA has shown a moderate aging rate. At 700 mA and 1,000 mA the depreciation of the luminous flux is rapid with –17% at 7,000 hours and continuously increasing standard deviation of 20 tested LEDs. For the case 85°C, the current 1,000 mA and also the current 700 mA are not recommended for using in long-term applications (e.g. street lighting installations). This contribution is very important for the discussion among the users and developers of the street lighting systems, that the aging rate is strongly depend-
ent upon the LED-type and LED-manufacturers and hard operation conditions like 700 mA and 1,000 mA should be avoided. The optimal current for white LEDs is about 550 mA according the research of the lighting lab of the TU Darmstadt.

**Figure 8**  Luminous flux degradation of the LED 2-type at 85°C

**Figure 9**  Extrapolation for determination of the L\textsubscript{70}-lifetime for LED 1-type at 700 mA and 85 °C

Using the aging data for 20 LEDs of the LED 2-type for \(I_i = 700\) mA and \(T_s = 85\) °C, the rated lumen maintenance time \(L_{70}\) can be calculated according to the algorithm of IESNA TM-21-11 standard (see [5]). According the Figure 9 the aging
behavior over time of the 20 LEDs is different and the lifetime $L_{70B50}$ is 46,900 hours. That means that the well-known lifetime of 50,000 hours or more can seriously be fulfilled with a current lower than 700 mA or at a lower case temperature. The same extrapolation procedure was also applied for the data of LED 2-type at the same aging conditions and is illustrated in Figure 10, from which it can be concluded that only 11,600 hours can be determined for the $L_{70}$-lifetime. This indicates the need to select and qualify the white LEDs of different LED-manufacturers for a concrete LED-street light luminaire development and to intensively communicate with the LED-manufacturers in the selection circle.

From the own research results and analysis it can be concluded that the most problems have their roots in the packaging part, dominantly in the silicone-phosphor-layer (Figure 11) and only a small fraction of them should be searched inside

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*Figure 10* Extrapolation for determination of the $L_{70}$-lifetime for LED 2-type at 700 mA and 85°C

*Figure 11*

Crack in silicon primary optic due to thermal overstress
the LED-chip structure. In comparison to other semiconductor products, LEDs have seldom shown a sudden failure, the degradation is expressed in a slower depreciation of the optical performance (e.g. luminous flux).

The author would like to thank the University for Applied Science Hannover (Prof. Homeyer) and Dipl.-Ing. Hristo Ganev (Technische Universität Darmstadt) for the productive performance of the aging tests and for the data and picture materials.

**Literature**


Streetlights: valuable but expensive assets for Cities

Streetlights are among a city’s strategic assets: providing safe roads, inviting public areas, and enhanced security in homes, businesses, and city centers. However they’re usually very costly to operate, and they use in average 40% of a city’s electricity spending. As the cost of electricity continues to rise and as wasting energy is a growing concern for public and authorities, it’s becoming crucial that municipalities, highway companies and other streetlight owners deploy control systems to dim the lights at the right light level at the right time, to automatically identify lamp and electrical failures and enable real time control.

Cities that create such controlled streetlight networks can not only save up to 50% on energy and drastically enhance the maintenance service and safety in the street, but also leverage the streetlight grid as the backbone of other smart city applications.
The cost of operating a streetlight network

The cost of operating a streetlight network is usually split into:

- **Electricity costs:** Table 1 provides the average price of electricity per kWh for citizens in the European countries and in China. The streetlight network is a city’s primary consumer of electricity, representing 40% of a city’s electricity spending. The number of streetlights, the wattage of the lamps and its ballast/driver, and the number of hours during which the lamp is operating (average 4,000 hours per year) all contribute to the total electricity cost.

**Example:**
The annual electricity costs to illuminate a city of 100,000 inhabitants is more than 1.3 M$ in most European countries.

<table>
<thead>
<tr>
<th>Rank</th>
<th>Country</th>
<th>Average US$ per kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Denmark</td>
<td>0.2708</td>
</tr>
<tr>
<td>2</td>
<td>Germany</td>
<td>0.2438</td>
</tr>
<tr>
<td>3</td>
<td>Belgium</td>
<td>0.1974</td>
</tr>
<tr>
<td>4</td>
<td>Sweden</td>
<td>0.1958</td>
</tr>
<tr>
<td>5</td>
<td>Austria</td>
<td>0.1930</td>
</tr>
<tr>
<td>6</td>
<td>Italy</td>
<td>0.1919</td>
</tr>
<tr>
<td>7</td>
<td>Ireland</td>
<td>0.1875</td>
</tr>
<tr>
<td>8</td>
<td>Spain</td>
<td>0.1851</td>
</tr>
<tr>
<td>9</td>
<td>Luxemburg</td>
<td>0.1747</td>
</tr>
<tr>
<td>10</td>
<td>Netherland</td>
<td>0.1696</td>
</tr>
<tr>
<td>11</td>
<td>Portugal</td>
<td>0.1666</td>
</tr>
<tr>
<td>12</td>
<td>China (Guangdong Province)</td>
<td>0.1505</td>
</tr>
<tr>
<td>13</td>
<td>UK</td>
<td>0.1449</td>
</tr>
<tr>
<td>14</td>
<td>Finland</td>
<td>0.1370</td>
</tr>
<tr>
<td>15</td>
<td>France</td>
<td>0.1289</td>
</tr>
<tr>
<td>16</td>
<td>Greece</td>
<td>0.1211</td>
</tr>
</tbody>
</table>

Table 1  Average price of electricity  [Source: IFRI 2011]

- **Maintenance costs:** Night patrols to visually identify failed lamps, replacing failed lamps, cleaning optics and maintaining the integrity and security on the electrical grid require crews of streetlight specialists and service trucks. More than 80% of the streetlights are equipped with high pressure sodium lamps with a lifetime under 3.5 years, i.e. 14,000 burning hours. The maintenance costs per light point varies enormously from one country to another, depending on cost
average salaries and service level agreements. In Europe, the average cost of maintenance is estimated to be in the range of 50 USD per light point per year.

Example:
The annual maintenance budget for a city of 100,000 inhabitants is more than 0.7 M$ in most European countries.

Streetlights cause carbon dioxide (CO₂) emissions

Besides being expensive, streetlights contribute to air pollution. Producing one kWh of electricity with a nuclear plant generates about 100 grams of CO₂, while producing one kWh of electricity from a coal plant produces up to 1 kg of CO₂. The production of electricity needed to power street lighting systems adds to carbon dioxide emissions (CO₂ is the principal “greenhouse gas”) and nuclear dust. Table 2, below, provides an estimate of electricity use and the associated CO₂ emissions for some countries.

<table>
<thead>
<tr>
<th>Country</th>
<th>Estimated number of streetlights</th>
<th>Estimated number of kWh per year</th>
<th>Estimated annual electricity cost for streetlights</th>
<th>Estimated annual CO₂ emissions due to streetlights</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.S.</td>
<td>&gt; 68 million</td>
<td>&gt; 30 billion</td>
<td>&gt; $2 billion</td>
<td>&gt; 15 million tons</td>
</tr>
<tr>
<td>European Union</td>
<td>&gt; 90 million</td>
<td>&gt; 52 billion</td>
<td>&gt; $4.7 billion</td>
<td>&gt; 20 million tons</td>
</tr>
<tr>
<td>U.K.</td>
<td>7.7 million</td>
<td>&gt; 4.5 billion</td>
<td>&gt; $420 million</td>
<td>&gt; 2 million tons</td>
</tr>
<tr>
<td>France</td>
<td>8.7 million</td>
<td>5.2 billion</td>
<td>&gt; $350 million</td>
<td>&gt; 600,000 tons</td>
</tr>
<tr>
<td>Brazil</td>
<td>14 million</td>
<td>&gt; 10.1 billion</td>
<td>&gt; $1.3 billion</td>
<td>&gt; 2.6 million tons</td>
</tr>
</tbody>
</table>

Table 2 Estimate of electricity use and associated CO₂ emissions

To get an idea of the CO₂ emissions and electricity budget of your city’s street-light network:

▶ Yearly CO₂ emissions for street lighting = (42 × N) kg of CO₂, where N is the number of inhabitants in your city.

Example:
252 kg of CO₂ per streetlight in average in Europe
4,200 tons of CO₂ per year for a city with 100,000 inhabitants

▶ Yearly electricity budget for street lighting = (13 × N) kUS$, where N is the number of inhabitants in your city.

Example:
1.3 MUS$ per year for a city with 100,000 inhabitants
The Challenge for Cities

One challenge facing cities involves increasing their attractiveness for companies and people, in a fast changing world. Providing a safe and secure environment, developing innovative services to citizens, contributing to a greener city and enhancing budget efficiency are amongst key priorities for many cities. As demonstrated by market studies (e.g. McKinsey – Lighting the way: perspectives on the global lighting market), more and more cities understand that their streetlight network may play a strategic role in helping them overcome these challenges, particularly to:

- Increase street safety: reduced lamp downtime and enhanced street visibility is directly linked to driver and pedestrian safety and comfort. Studies show how improved street lighting reduces crime and improve the feeling of being in a secured place.
- Improve maintenance processes: automatic lamp and electrical failure identification, monitoring streetlight cabinet and light points contribute to maintenance budget reductions, while improving lighting service quality.
- Reduce energy consumption and communicate on associated CO₂ savings 1) by deploying more energy efficient dimmable HPS and LED luminaires and 2) by dynamically adapt light levels, controlling and monitoring streetlight and streetlight switching cabinets. The rising price of electricity is, by itself, responsible for the majority of the increase in streetlight operation budgets. It’s now becoming strategic and compelling for cities to implement solutions to measure, analyze and reduce electricity use, decrease maintenance costs, challenge their energy providers and contribute to the reduction of CO₂ emissions, as required by the Kyoto Protocol.
- Leverage their streetlight grid as a backbone to supply energy to smart city equipment and to monitor environmental sensors and other electrical or communication equipment rather than spending money on additional civil works to deploy additional power cables. Unlike in the USA and the UK, the entire streetlight grid is switched off during the day in European
and Asian cities. Thus, these grids cannot be used to connect surveillance or traffic cameras, environmental sensors, information panels, EV charging stations, traffic lights, Wi-Fi spots, etc.

Retrofitting old inefficient high pressure sodium or mercury-vapor streetlights to LED lights and equipping them with “Dynamic Streetlight Control Systems” is the solution for cities to address all these challenges as demonstrated further in this document.

“In the outdoor application, simple timers were once the only type of lighting control system used, but this is now another fast-growing area. More dynamic lighting control systems are emerging to improve the economics of investment by governments and municipalities by maximizing energy savings as well as improving the lifetime of light sources. Dynamic lighting control systems can also enhance the safety or ambience of an area by adjusting light output according to the brightness of the natural light available.” (McKinsey market study – 2012)

Some cities have started to deploy LED luminaires and Dynamic Streetlight Control Systems but more will follow in the next years, as indicated in the McKinsey’s 2012 Global Lighting market study, summarized in the following drawing:

![Investment of LED basic-, Control System and new installations](image_url)

**Figure 1** Investment of LED basic-, Control System and new installations

Dynamic Streetlight Control Systems is a relatively new concept for cities. Without learning more about possible solutions, features and benefits, many cities may invest in proprietary solutions that become expensive stranded assets since they can’t evolve to smart city platforms in the future.

The variety of proprietary systems can make it difficult for cities to choose the best solution and, consequently, limits their ability to reduce energy and maintenance costs. Cities should not be dependent on a single vendor for such a strategic and long-life assets. To protect public investment, cities should specify open, interoperable and interchangeable solutions that are future proof and offer a better return on investment.
Solution: objectives, architecture, features

Objectives of a Dynamic Streetlight Control System

The main objectives of a Dynamic Streetlight Control System should be to:

- Reduce energy consumption
  - by switching ON/OFF at the right time
  - by dynamically adapting lighting levels at each light point to the light output required by the lighting standard, at fixed time and/or based on the activity in the area
  - by identifying energy theft on dedicated streetlight networks
  - by identifying current leakage on streetlight dedicated networks

- Reduce maintenance budgets
  - by replacing night patrols with automatic failure identification mechanisms
  - by enabling remote real-time control and monitoring to check any situation remotely rather than sending crews onsite
  - by assigning tasks based on failure reports to designated teams and by monitoring the performance
  - by identifying and transmitting to on-site teams the necessary spare parts to have on intervention, based on analytics of the failures

- Enhance safety, lighting and maintenance services
  - by identifying any failure on the network (lamp failure, segment failure, accident on a pole, cycling lamp, high/low power, high/low voltage, low power factor, etc. as fast as possible to reduce lamp downtime

Figure 2  Luminance Level
– by identifying cable theft which is an increasing issue in many countries
– by producing key performance indicators, reports and generating advanced alarms to anticipate any issue, identify potential problems and fix them before they become critical
– by monitoring the lamp’s burning hours to change lamps before they actually fail

![Maintenance Services as a result of technical information for each light point](image)

**Figure 3**

Use the streetlight network as the backbone of smart city applications
– by using the streetlight control system as a city-wide communication network to control/monitor any sensor and other devices through the same infrastructure
– by keeping the power ON during the day on dedicated streetlight networks in order to power videosurveillance cameras, WiFi spots, 4G (future 5G) base stations, environmental sensors and other electrical devices, instead of investing in additional expensive power cables and civil works to power these devices.

To fulfill such challenging objectives while being evolutive and future-proof, Dynamic Streetlight Control Systems must be based on open and standardized communication protocols that are:
Proven to be scalable to support city-wide networks for streetlights, sensors, meters and other devices
Known to address issues of large communication networks (e.g. security, dynamic routing, addressing)
Adopted by many manufacturers to offer a wide range of possible light point controllers, gateways, segment controllers, meters, sensors, digital and analog inputs and other devices.

System architecture for Dynamic Streetlight Control

To achieve the above objectives, the recommended system architecture is based on the following key components:

**Figure 4  System architecture for Dynamic Streetlight Control**

**Light Point Controllers – Key Requirements**

<table>
<thead>
<tr>
<th>Need</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Need to fit with any shape of luminaire</td>
<td>Light Point Controllers can be integrated either at the bottom of the pole or inside the luminaire.</td>
</tr>
<tr>
<td>Easiness of installation</td>
<td>Light Point Controllers should be easy for installers to install and to commission.</td>
</tr>
<tr>
<td>Low energy consumer</td>
<td>Light Point Controllers should consume less than 3 watts.</td>
</tr>
<tr>
<td>Feature</td>
<td>Description</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td><strong>Operation Temperature</strong></td>
<td>Light Point Controllers should support operating temperatures from −40 °C to + 80 °C to support temperature in luminaires and/or pole base.</td>
</tr>
<tr>
<td><strong>Switching control</strong></td>
<td>Light Point Controllers should embed one or more relays to switch the light point ON/OFF through the control system. Light Point Controller with more than one relay should be able to control decorative lighting or other loads connected to the same pole.</td>
</tr>
<tr>
<td><strong>Stepless dimming control</strong></td>
<td>Light Point Controllers should be capable of stepless dimming with the possibility to set the dimming level at any % (with accuracy of 1%). Dimming interface should be either 1–10 volts, DALI or PWM to fit with most of the LED drivers and electronic ballasts on the market. Dimming for electromagnetic ballast should be via voltage regulation and power factor control.</td>
</tr>
<tr>
<td><strong>Communicate using a standardized ISO protocol</strong></td>
<td>Light Point Controllers should implement bi-directional communication using a standardized ISO-approved protocol that is adopted by many manufacturers of Light Point Controllers to provide interoperability with different Central Management Software solutions. It should receive and execute real time switching and dimming commands. It should accept information reading commands and it should answer such metering reading requests in real time.</td>
</tr>
<tr>
<td><strong>Implement an internationally agreed functional profile such as the LONMARK profile</strong></td>
<td>On top of using a standardized communication protocol, Light Point Controllers should implement an internationally agreed functional profile such as LONMARK Streetlight Profile, agreed and implemented by multiple competing vendors, to offer end-users with a way to interchange Light Point Controllers from various vendors.</td>
</tr>
<tr>
<td><strong>Compatible (interchangeable) with other Light Point Controllers from other manufacturers</strong></td>
<td>By using a standardized ISO protocol, Light Point Controllers should be inter-changeable with other Light Point Controllers supplied by other manufacturers.</td>
</tr>
<tr>
<td><strong>Repeat the communication signal if necessary</strong></td>
<td>Light Point Controllers should act as signal repeaters to avoid the need to install additional signal repeaters/filters/couplers, to establish automatic mesh networks and to simplify the deployment of the systems.</td>
</tr>
<tr>
<td><strong>Detect various failures and alarms</strong></td>
<td>Light Point Controllers should be able to detect driver and lamp failure, low/high mains voltage, low/high current, low power factor, high temperature for LED luminaires, cycling lamps and day burners.</td>
</tr>
<tr>
<td><strong>Measure electrical values</strong></td>
<td>Light Point Controllers should be able to measure mains voltage, current, power, power factor and temperature (for LED luminaires).</td>
</tr>
<tr>
<td><strong>Measure cumulated energy consumption</strong></td>
<td>Light Point Controllers should be able to measure and store the cumulated energy consumption in kWh.</td>
</tr>
<tr>
<td><strong>Measure number of burning hours</strong></td>
<td>Light Point Controllers should be able to measure and store the cumulated numbers of lamp burning hours.</td>
</tr>
<tr>
<td><strong>Over the air software update</strong></td>
<td>It should be possible to upgrade Light Point Controllers’ embedded software via the communication network.</td>
</tr>
</tbody>
</table>
## Segment Controllers or Gateways – Key Requirements

<table>
<thead>
<tr>
<th>Need</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions and ease of installation</td>
<td>The dimensions of the Segment Controller should be compatible with the size of the existing streetlight cabinets in which it shall be installed. It shall be installed on a DIN RAIL to be compatible with most electrical installation standards. Wireless gateways may be installed in a different way and independent on the existing streetlight electrical cabinets.</td>
</tr>
<tr>
<td>Secured TCP/IP communication via any Ethernet media</td>
<td>The Segment Controller or Wireless Gateway should be able to communicate with the Central Management Software using secured TCP/IP over any Ethernet media including GPRS, 3G, 4G, WiFi, ADSL and Fiber Optic. Proprietary protocols are discouraged.</td>
</tr>
<tr>
<td>Remote configuration</td>
<td>The Segment Controller or Wireless Gateway should be capable of being remotely configurable through Central Management Software.</td>
</tr>
<tr>
<td>Operation Temperature</td>
<td>The Segment Controller or Wireless Gateway should support temperatures from –40°C to +60°C without any additional ventilation nor heating devices.</td>
</tr>
</tbody>
</table>
| Control and monitoring of streetlight electrical cabinets for dedicated streetlight networks | The Segment Controller should provide streetlight cabinet control features including:  
- Programmable astronomical clock  
- Mains switch control  
- Open door monitoring  
- Segment failure identification  
- 3-phase metering including power, voltage, current, power factor, energy and harmonic distortion (THD)  
- Support modbus extensions for additional digital/analog inputs |
<p>| Support open protocols that are implemented by several manufacturers  | The Segment Controller or Wireless Gateway should implement and support one or more standardized ISO protocols to communicate with, control and monitor any Light Point Controller that supports the same protocol. The Segment Controller or Wireless Gateway should support Light Point Controllers from several manufacturers, excluding itself. |
| Autonomous control                                                   | The Segment Controller or Wireless Gateway should control the Light Point Controllers autonomously, without any connection to the Central Management Software.                                                     |
| Open Protocol with the Central                                      | The Segment Controller or Wireless Gateway should be capable of communicating with the Central Management Software using standardized methods such as XML and HTTP messages. No proprietary protocols should be used in order to be able to provide interconnectivity and interoperability between different segment controllers and different Central Management Software Application from various competing software suppliers. |
| Group control and individual light point control                    | The Segment Controller or Wireless Gateway should provide ways to switch and dim groups of light points as well as individual Light Point Controllers.                                                           |</p>
<table>
<thead>
<tr>
<th><strong>Schedulers and calendars</strong></th>
<th>The Segment Controller or Wireless Gateway should enable many types of switching/dimming schedulers for each group of Light Point Controllers. It should enable the end-user to program switching/dimming schedulers during exception days (e.g. July 4th), exceptional periods (e.g. from July 1st to August 31st) and manage the priority between standard schedulers and exception schedulers. Schedulers should not be limited to a certain number of switching/dimming steps per night. Switching and dimming commands should be set either based on fixed time, based on astronomical time (sunset/sunrise + or – a time shift) or based on sensor-based scenario.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dynamic lighting</strong></td>
<td>Switching and dimming commands should be set either based on fixed time, based on astronomical time (sunset/sunrise + or – a time shift) or based on user-configurable sensor scenario.</td>
</tr>
<tr>
<td><strong>Push data to the Central Management Software</strong></td>
<td>The Segment Controller or Wireless Gateway should collect data from the Light Point Controllers and send/push them to the Central Management Software in an unsolicited way to ensure scalability and event-based data collect.</td>
</tr>
<tr>
<td><strong>Record historical data while no communication with Central Management Software</strong></td>
<td>The Segment Controller or Wireless Gateway should keep up to one month of data on its local flash disk if no communication with the Central Management Software</td>
</tr>
<tr>
<td><strong>Real-time clock management</strong></td>
<td>The Segment Controller or Wireless Gateway should provide a way to automatically synchronize its internal real-time clock with NTP servers. It shall automatically update its real-time clock when summer/winter time shift.</td>
</tr>
<tr>
<td><strong>Programmability</strong></td>
<td>The Segment Controller or Wireless Gateway should provide ways to add additional applications in the Segment Controller or Wireless Gateway, to support new smart city applications, develop other specific features or support new protocols.</td>
</tr>
</tbody>
</table>

## Central Management Software – Key features

<table>
<thead>
<tr>
<th>Need</th>
<th>Specified feature</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Multi-user Web Application Server</strong></td>
<td>The Central Management Software should be based on an open Web Application Server. Its user interface should be 100% Web-based and accessible from any computer on the network through various types of web browsers including Microsoft Internet Explorer, Safari and Chrome.</td>
</tr>
<tr>
<td><strong>Enterprise server and Cloud-based server</strong></td>
<td>The Central Management Software should be available to be installed on the city’s server as well as available, as an option, on a web-hosted server (i.e. cloud or SaaS model).</td>
</tr>
<tr>
<td><strong>Smart phone and tablet user interfaces</strong></td>
<td>User interfaces should be available for iOS, Android and Windows 8 phones and tablets.</td>
</tr>
<tr>
<td><strong>Based on open technologies</strong></td>
<td>The Central Management Software should be developed with open and standardized languages including Java, XML configuration files and SQL database. It should enable the development of additional features without the need to acquire any development software license.</td>
</tr>
<tr>
<td>Requirement</td>
<td>Description</td>
</tr>
<tr>
<td>---------------------------------------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td><strong>Open database engine</strong></td>
<td>The Central Management Software should record all the data in a centralized SQL database and should be compatible with MYSQL or PostgreSQL to avoid being obliged to purchase additional software license for database engine.</td>
</tr>
<tr>
<td><strong>User authentication system</strong></td>
<td>The Central Management Software should enable administrators to create, modify, delete users, passwords, groups and access controls. It should provide modern and efficient security features.</td>
</tr>
<tr>
<td><strong>Support multiple types of Segment Controllers and</strong></td>
<td>The Central Management Software should support most of the widely deployed powerline and wireless Control Systems, from various competing hardware suppliers.</td>
</tr>
<tr>
<td><strong>Wireless Gateways</strong></td>
<td>The Central Management Software should be able to provide interconnectivity and interoperability between solutions from different hardware manufacturers to guaranty independence between Central Management Software layer and field hardware layer.</td>
</tr>
<tr>
<td><strong>Support multiple models of Light Point Controllers from various manufacturers</strong></td>
<td>The Central Management Software should support configuration, programming, control and monitoring of many different types/models of Light Point Controllers from many competing suppliers.</td>
</tr>
<tr>
<td><strong>Support multiple languages</strong></td>
<td>The Central Management Software should support multiple languages and dictionaries shall be exportable and modifiable by the administrator of the system.</td>
</tr>
<tr>
<td><strong>Provide map-based inventory</strong></td>
<td>The Central Management Software should create any object (street-light, streetlight cabinet, sensor, meter, etc.) and enable users to group objects per geographical zone, to move, delete and duplicate objects on the maps.</td>
</tr>
<tr>
<td><strong>Compatible with multiple map sources</strong></td>
<td>The Central Management Software should enable the end-user to select the map source of his/her choice: Microsoft Bing, Google, Nokia map, ESRI, etc.</td>
</tr>
<tr>
<td><strong>Support multiple types of objects</strong></td>
<td>The Central Management Software should support Light Points, Segment Controllers, Gateways, Sensors, Electrical Vehicle Charging Stations, Weather Stations, Energy Meters and other types of objects to provide evolution to smart city applications.</td>
</tr>
</tbody>
</table>
| **Streetlight management related features**                   | The Central Management Software should provide streetlight-specific features such as:  
  – Programming and commissioning schedulers  
  – Real time control and monitoring of Light Point Controllers  
  – Real time control and monitoring of Streetlight Cabinet  
  – Big data and automatic data collect  
  – Data analytics including maintenance reporting, lamp failure analysis, energy consumption reporting, energy saving calculation, complex alarm triggering and notification, lamp lifetime analysis and data history analysis. |
| **Provide web service interface for 3rd party software**      | The Central Management Software should provide HTTP REST XML web service to interface with third party software. |

The key requirements listed above are issued from extracts of tenders from large cities such as Paris, Oslo, Dublin, Lyon, Jakarta and Brasov.
Analysis of the various systems available on the market

Categorizing available systems

The variety of systems available on the market can be categorized as follows:

► CATEGORY 1 – Non-managed LED luminaires: low cost LED manufacturers provide non-controllable non-dimmable LED luminaires. While such LED luminaires save an average of 35% energy when compared to equivalent high pressure sodium lamps, most of them have not proven to provide steady light output for more than few years. While the average LED lifetime is expected to be around 50,000 hours (against 14,000 hours for high pressure sodium lamps), streetlight maintenance companies still have to clean streetlight optics every 2 or 3 years in most large polluted cities. They also need to manage the growing number of electrical failures (e.g. growing inrush current with LED luminaires, cable theft, power theft), thus not achieving the maintenance cost targets promoted by LED manufacturers.

► CATEGORY 2 – Autonomous dimmable luminaires: (electronic ballast/driver with high pressure sodium lamps or LED lamps): autonomous dimmable luminaires are not much more expensive than non-dimmable luminaires but they consume about 25% less energy. Like Category 1 above, such systems do not address maintenance issues, nor enable cities to deploy smart city applications but they can be a first step if they provide with a way to upgrade to Dynamic Streetlight Control Systems.

► CATEGORY 3 – Streetlight cabinet control systems: Such systems are applicable only for dedicated streetlight networks where lights are switched by a master circuit breaker in the streetlight electrical cabinet. They are not applicable to the USA and UK markets. Controlling the streetlight cabinet increases remote control over ON/OFF times and helps identify lamp failures. But most streetlight cabinet control systems are not designed to extend to individual light point control using powerline or wireless protocols, not enabling cities to reduce their energy consumption. When used in conjunction with a segment “mains voltage variator”, suppliers claim to save up to 30% energy by reducing the mains voltage from 230 volts to 180 volts. It is important to note that electronic ballasts and LED drivers are not compatible with such mains voltage dimming technics, which makes mains voltage dimming obsolete on the market.

► CATEGORY 4 – Proprietary individual light point control systems: More than 50 suppliers have developed their own proprietary protocol (powerline or wireless) to communicate between their Light Point Controllers installed in each luminaire and their Segment Controller or Wireless Gateway. Each supplier had to make significant investments to develop Light Point Controllers, reinvent protocols, security, network routing, gateways, software and tools to manage each layer of their proprietary system. By using open systems
## Comparative study

<table>
<thead>
<tr>
<th>Feature</th>
<th>Open individual light point and cabinet control</th>
<th>Proprietary individual light point control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Some of the solution providers</td>
<td>Osram, Rongwen, Vossloh Schwabe, Citylone, Echelon, Amko, Thorn, Philips Starsense powerline, Apanet, Flashnet</td>
<td>Harvard, Telensa, Philips Starsense RF, Umpi, Roam, etc.</td>
</tr>
<tr>
<td>Energy Savings from dimming</td>
<td>Up to 45%</td>
<td>From 30% to 45%</td>
</tr>
<tr>
<td>Stepless Dimming</td>
<td>Yes</td>
<td>Not all (many are 2-step dimming)</td>
</tr>
<tr>
<td>ON/OFF control, scheduling and astro clock</td>
<td>Standard feature</td>
<td>Standard or optional feature</td>
</tr>
<tr>
<td>Real time remote cabinet control and monitoring</td>
<td>Yes</td>
<td>Most of these solutions only provide light point control</td>
</tr>
<tr>
<td>Real time remote light point control and monitoring</td>
<td>Yes</td>
<td>Yes, even if some of these systems are not bi-directional</td>
</tr>
<tr>
<td>Automatic lamp and other failure detection</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Alarms via Web portal/cell phone</td>
<td>Yes, including advanced alarms</td>
<td>Yes with most of them</td>
</tr>
<tr>
<td>Automatic energy saving calculation</td>
<td>Yes</td>
<td>Not all</td>
</tr>
<tr>
<td>Increased lamp lifetime</td>
<td>+20%</td>
<td>+20%</td>
</tr>
<tr>
<td>Support constant light output</td>
<td>Yes</td>
<td>Not with most proprietary solutions</td>
</tr>
<tr>
<td>Support sensors and dynamic lighting</td>
<td>Yes</td>
<td>No, except AEG and COMLIGHT</td>
</tr>
<tr>
<td>Compatible with open Central Management Software</td>
<td>Yes</td>
<td>No, except Paradox, Silver Spring Networks and Telematics</td>
</tr>
<tr>
<td>Smart city extensions</td>
<td>Yes</td>
<td>No, except Silver Spring Networks, Paradox and Telematics</td>
</tr>
<tr>
<td>Average price per light point</td>
<td>From $70 to $120</td>
<td>From $70 to $180</td>
</tr>
<tr>
<td>Estimated ROI</td>
<td>&lt; 5 years (from 2 to 8 years depending on price of kWh and lamp wattage)</td>
<td>&lt; 5 years (from 2 to 10 years depending on price of kWh and lamp wattage)</td>
</tr>
<tr>
<td>Feature level</td>
<td>9 / 10</td>
<td>5 / 10</td>
</tr>
<tr>
<td>Streetlight cabinet control with/without segment voltage dimming – CATEGORY 3 –</td>
<td>Autonomous dimmable luminaires – CATEGORY 2 –</td>
<td>Non-dimmable LED luminaires – CATEGORY 1 –</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Philips Amplight, Arelsa, Reverberi</td>
<td>Osram, Tridonic, Philips</td>
<td>Many low cost LED luminaires</td>
</tr>
<tr>
<td>Up to 20 %</td>
<td>Up to 30 %</td>
<td>No dimming</td>
</tr>
<tr>
<td>No, even with mains voltage dimming</td>
<td>Only up to 5 pre-programmed dimming levels</td>
<td>No</td>
</tr>
<tr>
<td>Standard or optional feature</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Yes, but cabinet control only</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Only for cabinet alarms</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>No</td>
<td>+20 %</td>
<td>No</td>
</tr>
<tr>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>No, except Arelsa</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>From $40 to $80</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>No ROI without mains voltage dimming, but then not compatible with LEDs</td>
<td>&lt; 8 years</td>
<td>&lt; 10 years</td>
</tr>
<tr>
<td>3 / 10</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>
every manufacturer benefits from existing code and availability of standard components developed and tested in other markets by many market players. Proprietary systems require massive investments from the supplier and consequently result in a solution with fewer features. But more importantly, proprietary systems are only supported by a single manufacturer. Would you purchase computers that could send emails only to computer from the same brand or print to their own printer? Would you purchase a camera that could take pictures that can only be displayed on a screen from the same manufacturer?

**CATEGORY 5 – open individual light point and cabinet control systems:**
When many manufacturers adopt a common, standardized communication protocol, making their products interoperable and interchangeable, cities have the choice between multiple products, while manufacturers have access to a larger market. Such solutions exist and can address both electrical cabinet control as well as individual light point control. In addition, since protocols are standardized, they can be used to control and monitor many other “Smart City” devices including sensors, energy meters, waste containers, water pipes, electrical vehicle stations, city information panels and more. Currently, the ISO14908 standard is adopted by more than 20 manufacturers who developed interoperable Light Point Controllers. With 20+ competing companies all using the same communication standard there are exciting new opportunities for cities and street-light maintenance companies to implement intelligent, dynamically controlled streetlight networks.

**Best practice: open individual light point and cabinet control systems**

With solutions described as in “Category 5” above, cities are able to start small today with cabinet control and later install Light Point controller to benefit from energy and maintenance services. Cities are not locked-in with any particular supplier and can benefit from any new compatible product released on the market. Currently, LONMARK International is the only organization that enables mixed vendor Dynamic Streetlight Control solutions.

The ISO/IEC 14908 control networking standard has played a pivotal role in transforming vertical markets in the automation world. From commercial buildings, public transportation systems, industrial plants to home automation, electricity metering infrastructure and Olympic venues, applications built on the LONMARK standard are everywhere. Millions of devices have been installed around the world in home, building, and utility automation systems. The platform’s proven system architecture scales to millions of devices. For example, more than 27 million homes in Italy are connected to a smart energy infrastructure using power-line signaling technology.

Cities, manufacturers and maintenance operators have adopted LONMARK based Dynamic Streetlight Control Solutions for the following reasons:
Open and multi-supplier: More than 20 hardware manufacturers offer compatible Light Point Controllers. All these modules are compatible with each other, can be mixed on a streetlight segment and controlled by the same Segment Controller or Gateway. In case one fails, it can be replaced by another one from another manufacturer.

Cities cannot afford to waste public investment. Thus, they can’t engage budget in proprietary systems. Here are a couple of examples of street light projects.

In 2009 an installer selected a wireless light point control system and planned to provide this system to a city as part of a Public Private Partnership contract. After 2 years of trials, technical problems and tests in the streets, with major investment from the installer (trucks, people, time) and penalties from the city to the installer, the proprietary wireless control system supplier filed for bankruptcy. The installer had no choice but make additional investments to uninstall the whole system. They replaced it with an open system based on the LONMARK interoperability standard. The system was installed in a few days and provided the expected energy and maintenance savings expected by the customer.

In 2013, the city of Paris decided to deploy interoperable Light Point Controllers in several parts of the city. The city’s contractor started to select qualified Light Point Controllers. They could select 4 vendors/models from Osram, Citylone, Rongwen and Lumnex that are all compatible with each other and can be mixed on various projects.
Proven and robust: There are over 450 successful projects and more than 700,000 light points installed in 15 countries (i.e. estimated 60% market share). Thousands of control applications based on the LONMARK interoperability standard are in use today in homes, offices, plants, transportation and other markets in Europe, America and Asia. LONMARK certified products used in powerline networks even operate in areas with poor powerline communication quality. Unlike some proprietary protocols, it provides control and monitoring (bidirectional communication) to enable lamp command and feedback. Installations have been installed on dedicated electrical networks (such as those for streetlights) as well as mixed electrical networks (such as those that supply houses and buildings, as well as streetlights like most of the cities in the U.K.).

Evolutive from cabinet control as well as light point control: cities can control their streetlight cabinets to benefit from maintenance enhancements at low cost. Cities such as Oslo and Paris decided to deploy smarter cabinet controllers, to have the opportunity to later extend to light point control and get the full benefits of the solution.

Available with Powerline and soon Wireless IPv6: most Dynamic Streetlight Control Solutions currently installed on the market based on the LonMark interoperability standard use powerline as the primary communication media. Wireless devices supporting IPv6 addressing is currently being tested and should be released soon.

Dynamic lighting: the LONMARK platform and associated Central Management Software enables users to define a sensor-based system. Thanks to broadcast and peer-to-peer communication capabilities, LONMARK based solutions enable sensor-based “train of light” or “follow me” lighting scenarios to save even more energy, while keeping the right light level at the right time.

Smart city applications: sensor manufacturers can easily implement products and systems based on the LONMARK interoperable protocols to sell and install sensors on streetlight poles, that can benefit from the existing streetlight control infrastructure to collect sensor data, trigger alarms, generate reports and other applications.

Best practice: open Central Management Software

Central Management Software is required to configure, install, control and monitor a streetlight network from anywhere – a central Network Operating Center, a city or contractor’s office or a service car – at anytime. As shown in each streetlight control project, the Central Management Software, also called Streetlight Control and Monitoring Software, is an essential part of the overall solution. It provides valuable insight at each project phase: proof of concept, installation of the first field project, organization of the deployment, confirmation of the ROI and verification of deployment and maintenance tasks.
An important aspect of using this type of application is that it allows the user to define administrative units in order to manage different deployments in different geographical areas. Each user has access to its own area, while the supervisor manages all installations, everything incorporated in the same software application.

Central Management Software creates new business opportunities for street-light maintenance contractors to provide Network Operation Centers where they operate the Central Management Software as an online service (Software as a Service – SaaS – or Cloud), from where they can manage multiple cities to lower overall costs. Also, the software supplier must provide to the end-user the possibility to purchase the license of the Central Management Software in order to install it on his own server.

Central Management Software is key in PFI/PPP (Public Private Partnership) contracts, where PPP contractors are committed through binding service level agreements and minimum energy savings. Central Management Software provides neutral key performance indicators to both the city and the contractor. It enables the PFI/PPP contractor to manage dimming levels, i.e. energy consumption, according to their energy savings commitment and evolution of the price of energy during the PFI/PPP contract timeframe (from 10 to 25 years). It also enables them to manage their maintenance budget, control luminaire suppliers by analyzing the behavior and energy consumption of their products.

The Central Management Software is also a bridge between streetlight assets and the city’s existing IT system and business processes. With web-service based Central Management Software as specified in the previous section, all data collected are transformed into valuable information and services that are available for work-order management applications, energy billing systems, geographical information systems and smart city platforms. The Central Management Software hides the technical complexity of underlying hardware and protocols for end-users and such third party systems.

**About the LONMARK International Organization**

LONMARK International enables an evolution in street lights whereby smart communicating luminaires offered by a variety of suppliers can be connected in a single wired or wireless network. LONMARK International is a member-based organization that publishes guidelines and certifies products for conformance with the ISO/IEC 14908 series of standards for networked control. This standardized approach reduces the cost of installing and supporting systems over their lifetime by eliminating proprietary solutions offered by most vendors today.

LONMARK International is expanding its industry recognized interoperability guidelines and device profile architecture to support the rapidly growing market for Industrial Internet of Things (IIOT). This new standards-based architecture will expand the number of connectivity options for street lighting networks leveraging the proven LONMARK interoperability model.
To learn more about LonMark International and its street lighting initiative, please visit [www.lonmark.org/connection/solutions/lighting/streetlighting](http://www.lonmark.org/connection/solutions/lighting/streetlighting).

**Customer Case Studies**

**A scalable solution for small to large cities**

The best practices as described earlier are adopted by many streetlight maintenance operators, manufacturers and cities in China, South East Asia, Australia, South America and Europe. LONMARK based solutions are not only designed for large cities. The benefits apply to cities of all sizes:

- **Smaller cities** such as Sénart en Essonnes, whose streetlights are monitored by professional streetlight maintenance operators can also take full benefit of the same system. Thanks to the Streetlight.Vision Central Management Software, streetlight maintenance operators can mutualize the overall cost on many smaller cities in a single Network Operating Center. Cities access and display information related to their own streetlight network, while maintenance operator can have custom views of the installed systems.

- **Large cities** such as Oslo, Norway, have reduced the overall costs associated with their streetlight network by almost 50%.

Solutions are deployed in more than 450 cities in 15 countries including Paris, Lyon, Metz, Brest, Rouen, Moissy, Sénart (France), Barcelona, Badalona, Terrassa (Spain), Portuguese Highways (Portugal), Polish Highways (Poland), Arahova (Greece), Dublin, Cork City (Ireland), Oslo, Trondheim (Norway), Cadeyreta (Mexico), Porto Alegre (Brazil), Santiago (Chili), Jakarta (Indonesia), Dongguan, Cheng’An, Forshan, Guangzhou, Wuxi (China), Daejon (Korea), Christchurch (New Zealand), Adelaide, Perth (Australia), etc.

Find additional informational about other customer case studies below:

- **Multi-Vendor Project of the Year for 2013** – Small repeatable Solution: Guangdong Rongwen Lighting Co., Ltd for District of Guancheng in Dongguan, China. Guangdong Rongwen retrofitted the street lighting system of the district of Guancheng in Dongguan, China as part of a larger initiative of creating intelligent, efficient and low-carbon city management solution. Leading the upgrade, the Dongguan Guancheng Utility Service Center was tasked with replacing nearly 12,500 street and alley lights while integrating an intelligent control system that communicates with the greater city management system: [www.lonmark.org/connection/case_studies/documents/Guancheng%20Case%20Study_v2-1.pdf](http://www.lonmark.org/connection/case_studies/documents/Guancheng%20Case%20Study_v2-1.pdf)

- **SPIE**, a large installation and maintenance company with dedicated services for street lighting, fulfilled 6 Public Private Partnership contracts with cities in the south of Paris, France, thanks to the LONMARK solution provided by Streetlight.Vision, resulting in savings on energy, maintenance costs...

- Oslo, Norway, a pioneer in saving energy on their streetlight network has deployed LONMARK based streetlight control solution with Streetlight.Vision. More about the Oslo project at: www.lonmark.org/connection/case_studies/documents/Oslo_Streetlighting.pdf

- The well-known Place Bellecour in Lyon, France, is part of a global renovation project launched by Grand Lyon, that includes renovation of public lighting led by the French light engineering office “Les Eclairagistes Associés”, based on a LONMARK solution provided by Citylone: www.lonmark.org/connection/case_studies/documents/Bellecour_Place_Lyon_Streetlighting.pdf

- Dutch highways: In view of plans to introduce a high-speed train, the Dutch government decided to renew a major part of the A16 highway between the Galder and Klaverpolder junctions, a distance of 23 km, and to build four major cloverleaf highway junctions. Implementation was delivered by the Philips Tele-management team. More information about this project at: www.lonmark.org/connection/case_studies/documents/Netherlands_StreetlightingA16.pdf

- Using Flashnet’s street lighting management system, Brasov becomes the first Smart City in Romania. By the end of 2014, 10.481 street lighting fixtures across 399 streets in Brasov will be remotely controlled by the Flashnet’s solution, but the financial savings have already been observed after the installation of the first equipment: the energy costs are already reduced by 30%, while overall operational costs decrease by up to 42%. As Flashnet’s solution is based on open protocols, it provides complete compatibility and interoperability with multiple vendor agnostic controllers, sensors and countless Smart applications, thus providing the potential to evolve into a complete, future proof Smart City infrastructure, one of the first in Eastern Europe: www.lonmark.org/connection/case_studies/documents/Brasov20Case20Study-1.pdf

Take your share of a fast growing market

Due to the growing awareness of climate change and the rising cost of electricity, cities are deploying solutions that have proven to save energy and increase service quality, while enabling future possibilities.

Rapid Market Growth for the LONMARK based Solution:
a market opportunity for you

The number of installations in Europe and Asia has grown rapidly in the last few years. Streetlight maintenance companies are rolling out LONMARK based solutions in more and more cities every day. Cities now benefit from a significant catalog of more than 30 different models of interoperable Light Point Controllers from various manufacturers (Osram, Rongwen, Thorn, Philips, Citylone, Amko, Apanet, Sysplug, Lumnex, etc.), which are compatible with all LED dimmable luminaires, HID electronic dimmable ballasts and even with HID old magnetic ballasts.
Back in 2006, there were only 4 manufacturers of LONMARK-compatible Light Point Controllers. Today, there are more than 20 manufacturers supporting the LONMARK technology. There were less than 10 streetlight maintenance operators trained to the system in 2009, while today there are nearly 50 maintenance companies.

The Streetlight Control market is now becoming a high-volume and high-value market. From 90 M€ in 2012, it is expected to reach 256 M€ in 2016 and 494 M€ in 2020 (McKinsey – Global Light Market study – 2012). For manufacturers involved in the streetlight industry, outdoor environmental sensors or maintenance operators, this is an exciting high growth market opportunity.

**Extending the network beyond streetlights**

LONMARK based solutions make it possible to easily extend the solution to collect environmental data such as pollution ratio, humidity, temperature, car traffic, energy, gas and water meters, street noise levels, etc. Cities can use this information to increase their knowledge database for strategic planning. With LONMARK based solutions, the investment to install the infrastructure (segment controllers, telecommunication network and Central Management Software) can be reused for many other applications.

Thanks to its openness, the LONMARK platform is a strategic tool for cities to increase their control while optimizing their budgets and saving energy. Dynamic Streetlight Control Solutions also offer maintenance operators and other service companies a unique and strategic opportunity to develop new added-value services and new profitable business models.

Most streetlight maintenance operators are starting to take advantage of such open solutions and share the financial rewards with cities by creating strategic Public Private Partnerships. Through such contracts, streetlight maintenance companies are gaining control over public infrastructure projects and can later operate this infrastructure for other applications, such as traffic control, environmental data collection, to support advertising panels, EV charging stations or WiFi spots.

The same maintenance contractors have also started to provide cities with a full service package to resell Lighting as a Service, which require drastic control over each individual light point. Open Dynamic Streetlight Control Solutions enable new business models, offering early adopters a strategic differentiator and attracting new players that are active in adjacent vertical markets.

*Control networks based on LONMARK interoperability standard are fundamentally changing the way we think and interact with the devices that surround us.*
Will Changes in Control Technology Spark A New Street Lighting Era?

Jörg Schneck

Germany’s first permanent electrically powered streetlights were installed in Nuremberg and shortly afterwards in Berlin in 1882 (Source: German Wikipedia). Ever since, street lighting has been switched on at night and off again in the morning on an almost daily basis. In Germany alone, the annual energy consumption of street lighting systems totals roughly 4 Terawatt hours and with that accounts for about 0.7% of the total consumption of electrical power.

Operators requiring a better control system will first have to become familiar with conventional system structures. Analyses show that very different street lighting control technologies have been developed to suit local conditions. In the main, a difference is made between structures with luminaires (*LP for short*) that are connected to their own lighting cable and are switched in unison (Figure 1 [X1]) and those with luminaires that are permanently supplied with voltage via a mains cable and feature their own control electronics (Figure 2 [X2]).

![System setup of municipal lighting in the vicinity of buildings](image)
However, the various transfer methods that have become established over the years, which serve to transmit signals to either a sub-distribution point or to a luminaire, have resulted in even greater control system diversity. In the simplest case, a control line is used to switch the system. In order to keep the need for cabling to a minimum, this control line is extended by using a so-called repeat function. This means that the lighting cable is laid to its next sub-distribution point (SDP for short), from where it in turn addresses a contactor that then switches a new lighting cable.

As an alternative, so-called audio-frequency ripple control or longwave ripple control receivers can also be used. These do not require any complicated additional cabling due to a difference in the way signals are transferred to an SDP or LP. A list of common technologies, some of which can be freely combined, is presented in Figure 2.

![Typical structures of street light management](image)

*Figure 2  Lighting control system structures*

The above list of most commonly used technologies goes to show that they mainly deal with the topic of transmitting digital switching signals, which are sent in a weather- or time-dependent manner (to turn the system on or off). If, however, there is a need to improve the future efficiency of a lighting control system or to receive diagnostics data on the system as quickly as possible, the introduction of a light management system (LMS for short) will become a topic
of discussion. Many questions will then need to be answered – questions with which most operators will never have had to deal before, either because the technologies involved are new and innovative or because the necessary investments are considerable and/or such decisions have to be planned with a view to the long term. What will the envisaged LMS be expected to do? What’s the plan for data migration, which is to say what’s the best way to handle the conversion to the new system? Are there any standardised systems? Is it better to run with powerline or radio-controlled (wireless) technology? The list goes on…

Converting a larger system in the region of several thousand light points within a short space of time will therefore remain impossible for the vast majority of operators. The reasons can both be found in the financial outlay and the logistical effort involved, which is also why long-term availability plays such a key role.

**Defined Light Management for Outdoor Lighting**

As already inferred by the word “control”, such systems work in a solely unidirectional manner. All signals flow in one direction, as shown in Figure 3 [A] where luminaires are being switched on and off. The provision of any sort of feedback is not a feature of the system architecture – unless a service point is installed so that residents can be used as a feedback channel in the event of an LP failure. If such a feedback channel is professionalised as a technical feature of a system, it results in a light management system, see Figure 3 [B].

![Figure 3](image_url)  
*Figure 3  Differentiation in the field of lighting control*
Furthermore, for such a light management system, it is immaterial whether only the failure of a lamp is reported or if a whole bundle of data is sent to the process control technology. In the final analysis, the question becomes moot since the necessary work to provide the feedback channel determines the price and not the ultimately transmitted data volume.

The imminent technology change towards bidirectional communication is set to make the available options considerably more numerous. At the same time, though, the search for the best LMS will become substantially more difficult since a plethora of questions will have to be posed and answered in advance. Certainly the most important of these questions mainly concerns cost-effectiveness with regard to the additional cost compared to a conventional control system. What form will this additional expense take and what and/or where can savings be made? In the past, the main argument in favour of a light management system lay in the optimisation of maintenance tasks. But this has been almost completely eclipsed by the new trend towards using LED luminaires for outdoor lighting. With service life expectations of 50,000 hours and more, the topic of luminaire failure has become unimportant.

Instead, constantly rising energy costs will ultimately predicate the technological shift. Quick-response lamps whose efficiency rises when they are dimmed should be in a position to satisfy these new requirements and, in turn, stand up to the scrutiny of cost-effectiveness calculations. But to ensure luminaires can be operated as efficiently as possible, they must be integrated into a control loop. An example of such an extension can also be seen in Figure 3 [C]. Apart from the LMS itself, the topic of street lighting management should take on the same degree of importance and use as it already enjoys in the field of professional facility management. However, the future savings potential of such management systems lies in more than simply facilitating control of and feedback on defective light points via the process control technology, but can much rather be found in enabling street lighting to be managed in direct response to diverse parameters and events, such as:

- ambient brightness,
- road conditions,
- reflections (rain/dry road),
- fog,
- traffic-free and/or pedestrian-free street,
- pedestrian crossings that draw more attention to themselves by changing the colour of the lighting when a person actually crosses the road,
- flashing luminaires to alert approaching motorists that an accident has occurred behind a curve,
- etc.

To ensure the most cost-effective operation of street lighting, the above-named parameters should be taken into consideration when designing future light management systems.
In addition, the development of suitable sensor technology is set to become critical for such light management systems and thus takes on a special role. Light sensors that are capable of adjusting lighting levels or switching lighting on or off when triggered by defined ambient brightness levels constitute the current benchmark. However, if the various expectations that a lighting system as a whole is required to meet are taken into account, the parameters governing when the system could be switched or dimmed, if this were an option, are much more complex. Lighting for pedestrian crossings, by-roads, main roads, residential areas and access roads to rarely frequented areas (sports stadia) could be perfectly managed if it were possible to specify respective lux values in the overall system and if suitable motion detectors existed that could satisfy the needs of the segment.

However, perfectly managed systems that not only satisfy the above-mentioned points, but also fulfil other expectations have only been implemented in very few pilot projects because the necessary sensor technology is currently unaffordable. Motion detectors such as those used for facility management purposes are unsuitable for street lighting. Sensors that are suitable for the respective luminous density are currently only available for tunnels, but are equally too expensive for comprehensive use in street lighting.

One way to make the high sensor price tolerable is to interlink luminaires to form groups, which then makes it possible to spread the cost of one sensor over several light points. The evolution of the respective standardisation landscape will then also prove to be critical to ensure users have recourse to specifications for planning purposes. No planner will be prepared to take the risk of introducing an innovation for which no supporting standards exist.

**Standardisation, Extendability of Light Management Systems and Investment Security**

The best example of standardisation chaos was delivered at the end of the 1970s with the development of three different video systems: VHS, Betamax and Video 2000. And the performance was almost repeated with the extension of the DVD standard at the beginning of the twenty first century. While deciding to run with the wrong technology is – at worst – annoying when a person buys a smartphone, a wrong decision made in the public sector in favour of introducing a future LMS would have very serious repercussions for an operator.

Apart from the financial outlay for the product itself, the calculation of overall costs should equally take installation and commissioning costs, the expense of setting up the infrastructure as well as the costs of data transmission and staff training into consideration. At the same time, account should be taken of the degree of investment security with regard to the future evolution of the selected technology, product availability and standardisation, whereby the final point should be given special priority.
As described above, an LMS could make a significant contribution to saving energy. But how can competitiveness and product innovation be ensured down to the lowest automation level if the requisite interfaces are either unknown or have yet to be standardised across all manufacturers?

Functional invitations to tender should also become a standard feature when it comes to light management systems to ensure that various products/manufacturers can be integrated into the system as a whole. The more the field level becomes standardised, the more customers will be able to use such provisions to create an open, modular system without being tied to any particular manufacturer.

However, it will initially be necessary to clarify the fundamental technological question of which data transfer method to choose for the LMS. How is bidirectional data transmission to be effected in the field?

- Wirelessly
- or
- via a powerline (data transfer superimposed on the power supply line)?

With the powerline method, the luminaires’ power supply line is simply used for data transfer purposes, thus enabling continued use of the existing infrastructure. All luminaires that are electrically connected to the same cable can then be grouped to form a single control segment.

As an alternative, wireless data transmission comes with the advantage over the powerline solution in that the cabling infrastructure is unimportant. There are countless pros and cons for both of these competing technologies, which in almost every case will need to be individually discussed with the respective street lighting manager to elaborate which of the two options actually offers the better solution for the project at hand.

Depending on the choice of technology, though, care must also be taken to check on which definition and/or standard the product and/or the communication is based. The questions to be asked are whether the type of data transfer is open, whether a functional description for the respective product exists and whether interchangeability is given as is, for instance, the case with electronic ballasts in the DALI segment?

In the field of powerline data transfer, the European EN14901.1 and .3 as well as the American ANSI EIA 709.1 and .3 counterparts are the currently established standards. These standards are supplemented by the so-called profile definition for outdoor luminaire controllers in accordance with the LonMark® OLC specification. Various manufacturers have already used this as a basis to develop luminaire controllers that almost fully satisfy the above-mentioned demand for standardisation. Moreover, this has enabled real interchangeability at product level.
In a typical 3-tier lighting system, communication needs to be effected between the luminaire controllers (LC) or the pole controller (PC) and a data concentrator (DC). This system architecture has proved itself to be robust since the DC ensures that the lighting system continues to function even in the event of system failure (communication breakdown to the process control technology). In such an event, the system would go from weather-related management via the process control technology to time-dependent control with the aim of ensuring continued provision of basic lighting levels. The generated data would also be provisionally stored in a so-called data logger for several days without causing any data loss.

The data concentrators are typically connected to the process control technology using the internet protocol (IP for short), the advantages of which we experience every day: extreme robustness, open specifications, absolute technological standardisation and, naturally, availability for various communications channels:

- cable (Kat5),
- single/multimode fibre optics cables,
- wireless via GPRS and other local country-specific standards,
- satellite,
- broadband powerline with speeds of up to several 100 Mbit/s,
- etc.
The process control technology is used to manage the controllers distributed in the field. As different systems had been developed by various manufacturers over time, this was another area in which the need for further standardisation between the field and process control level became apparent. Efforts undertaken to this end were then consolidated in the TALQ initiative, which sees manufacturers jointly seeking to define a uniform communication standard. The aim is to ensure that the ultimately chosen process control technology will permit the integration of various subordinate field systems.

In the past, it proved to be difficult to establish stable communication between a data concentrator and luminaire controllers, with the problem being that power supply lines were primarily designed to carry energy from point A to point B, but were unsuitable for transferring data. The fact that reliable data transfer is now possible after all is mainly owed to a lot of research and development work into powerline data transfer technology and, ultimately, to advances made in the field of microcontroller technology. But as mains power supply lines are subject to highly varied loading and are prone to interference from various devices, it is difficult to define the transmission range. Thanks to so-called repeater technology, though, which automatically repeats heavily attenuated signals, it has now become possible to ensure data transfer quality of almost 100%.

In the field of wireless technology, systems are structured in a similar manner as in the field of powerline technology so that they equally feature a field level with luminaire controllers, a data concentrator and superordinate process control technology. However, the problems that wireless technology faces are similar to those besetting powerline technology, although different influencing factors come into play that need to be taken into account, such as:

- screening due to buildings,
- signal attenuation due to distance from the transmitter,
- sources of interference in the same frequency range,
- fog, snowfall, rain,
- foliation from trees,
- reflections,
- etc.

Solutions for all of the above-named influencing factors must be found if a wireless system is to ensure stable communication. Similar to the repeater technology found in the PL sector, so-called meshed technology has established itself for the purpose of networking controllers in the field for the wireless sector. However, this area has also seen the development of various competing technological solutions, as a result of which the customer’s decision-making process is made all the more difficult. Examples in this context are the mesh-supplemented 6LoWPAN as a sub-technology of the IP protocol and ZigBEE, another mesh-based technology with its origins in the field of facility automation. But making any forecasts whether either of the two competing standards will achieve dominance is extremely difficult at the present time since various highly renowned...
companies are currently seeking to strengthen their market position. One point does, however, stand out: there is no need to convert the IP protocol via a gateway when using 6LoWPAN, which could come with certain advantages.

Unfortunately, standardisation has not come as far in the field of wireless data transfer as it has in the field of powerline communication since manufacturers have been unable to agree on a common solution. All of the systems that are currently on the market naturally work within regulated open frequency ranges. But these frequency ranges are also open to everyone else. These ranges are not to be confused with the commonly known frequency bands as they are used for TV or radio. If a frequency range is open for control technology, it is also open to everyone else. Whether any given frequency is then used to operate a garage door, a remote-controlled electrical plug, the alarm system in the house next door or to provide wireless headphones with a continuous audio signal is immaterial. That means that the available bandwidth for data transfer can vary significantly. Since any given channel remains available for everyone, the available bandwidth necessarily has to be distributed among all users. At the same time, security measures need to be put in place to render communication tamper-proof. Cable-based communication, and in this context especially lighting cables, pose less of a problem with regard to data bandwidth and security since they are mostly laid underground and are therefore better protected against unauthorised access.

Figure 5  Typical 3-tier communication structure for light management
In line with the current state of the art, the systems on the market provide the following control-technological properties:

- switching on/off and dimming individual luminaires and luminaire groups,
- emergency operation features in the event of communication breakdown (provided that the power supply to the cable is not interrupted),
- balancing out a lamp’s decrease in luminous flux,
- a feedback channel to transmit the following measured values to the process control technology:
  - voltage,
  - current,
  - power factor,
  - output,
  - energy consumption,
  - lamp lighting hours,
  - luminaire temperature (provided that the luminaire features a built-in controller),
  - temperature of the electronic ballast (provided that the DALI ballast can supply these parameters) and
  - a list of all errors, i.e. any noncompliance with limit values of specified parameters, that are detected by the controller as well as an additional interpretation of the respective noncompliance, such as lamp failure.

Street lighting is poised to undergo a minor revolution. Luminaires will become dimmable, magnetic ballasts are ready for retirement and electronics are gaining ground, something that was simply unthinkable years ago. But exactly how and with which options future control technology for street lighting will be equipped depend on a huge array of factors, some of which may well have nothing primarily to do with the topic of street lighting. Making use of the existing street lighting infrastructure seems to be nudging its way into corporate focus and is in turn, quite coincidentally, responsible for giving us light at night.

The coming years will be exciting to experience and I therefore hope the above succeeded in informing you of at least some of the buzzwords and aims currently being pursued by the industry.
Smart Energy Saving with Motion Sensing Streetlight Control

Safety through good lighting that illuminates only when and where it is needed

Comlight

Light is essential to maintaining the balance of life. It directs the biological clock and brings energy and safety to the everyday life, but lighting is also responsible for one fourth of all electricity consumption worldwide and generates huge amounts of energy wastage due to non-beneficial lighting. In fact, lighting swallow up almost twenty percent of the total electricity expenditure in a typical built up area, and generates pointless waste of energy involving fully illuminating roads at times when there is no traffic, and lighting streets and public areas when there is no one around.

Street lighting has a significant effect on traffic safety, but at the same time this lighting is very energy demanding. With the ever-increasing focus on what can be done to reduce energy consumption, the most important energy-saving measure has been to replace existing luminaires with LED lights and dimming functions. An increasing number of municipalities are starting to look at possibilities to cut energy consumption, and thereby costs, by switching streetlights off completely, then the question of the impact on traffic safety arises.

Comlight, an innovative Norwegian company, believes that light should be provided only when and where it is actually needed. The company asks the question on how to make use of the advanced LED light technology to solve the core problem; the pointless waste of energy involved in fully illuminated roads and public areas when no one around.
In 2007, based on one simple idea, how to optimize the use of street lighting, a unique solution to the problem was created. After years of extensive research and product development, the “Motion Sensing Streetlight Control” system was presented. The system saves large amounts of energy and provides light only when and where it is needed without compromising safety. Today the company is a commercial technology provider on the international market, and has already won a number of prizes for its innovation and has garnered significant media coverage.

**Comlight’s Solution**

It’s all about having optimal light when needed. This is a well-known concept for indoor lighting where simple infrared sensors are used. Such a solution is not compatible with outdoor use where there is an excessive amount of noise sources, varying weather conditions, high speeds, and much more to take into account. Comlight has done something about these issues and with a patented advanced technology created a unique and robust detection system that is sensitive to all shapes and speeds and adapts to the actual situation. It only registers the activity that is relevant for safety – nothing else.
Each street light features a Comlight Eagle Eye, a radar detector that senses all activity that requires optimal lighting on the road or in the area. It gives full illumination when needed, but dimmed down or turned off, when no one around to save energy. The intelligent system automatically activates as soon as any vehicles or pedestrians are detected in the area and the detection is communicated wirelessly by radio for forward light triggering, creating a “light wave”. As a result, drivers, cyclists and pedestrians experience normal illumination levels all along their route. For drivers, it would appear to be lit as normal, but if looking down from an aerial view, an actual “light wave” is guiding the car. This system saves lighting operators considerable amounts of energy while also providing optimal lighting safety.

**Comlight Eagle Eye & Detection**

Comlight Eagle Eye is simple to install, saves energy and maintains safety at the same time. The system is completely maintenance free and the radars are produced to sustain various weather conditions with operating temperature range –30 to +60 °C. The Add-On solution makes it possible for the system to be retrofitted on existing lighting equipment at the same time as the luminaires are all being replaced or upgraded. The Eagle Eye is easily fitted to the streetlight with cable connection and rear cover.

![Figure 3](image)

**Technical Data**

- **Supply voltage:**
  Nominal 100-240 VAC,
  Range 90 - 264V (universal input),
  47 - 63 Hz

- **Power consumption:**
  approx. 1.5W (peak 4W with GPRS module)

- **Operating temperature:**
  -30°C to +60°C

- **RF Communication:** 900 MHz
  band (ISM), programmable
  up to +12 dBm
Another alternative is for the Comlight technology to be integrated into the luminaire. The system is universal and is suitable for all ballast solutions (1–10 V, DALI and StepDIM). It can be adjusted to suit various heights or diameters of pole and varying distances between the lights. The adaptive noise cancellation system is adaptive to its surroundings by movement and will activate normal operation during light precipitation and high intensity light will temporarily activate during heavy precipitation.

The detection area will depend on size and speed of the moving object and the height of the light pole. The system detects objects moving from 2 km/h to 200 km/h and the detection algorithms separate object detection into two separate data channels, for slow and fast moving objects. This gives the possibility to customize settings like light levels when detection in different channels and number of luminaires activated around different objects. The detection area will cover all normal luminaire installations.

Eagle Eye can work as a completely stand-alone system and can optionally be connected to a Central Management System through GPRS connection, or interfaced to any third party management software. The system can be set up with optional number of luminaires to be activated when movement is detected. For each installation, the optional Eagle Eye with GPRS module can be set up for communication to remote CMS, system set-up and statistical data.

**Figure 4** Detection Area
The GPRS allows remote access to both parameter settings and historical data such as the number of streetlights to be included in the “light wave”. This will depend on the distance between them, how far ahead it is important to be able to see and the road layout. The light intensity can be adjusted remotely, making allowance for variations like for example 20% – low intensity light (dim)/100% – high intensity light (full brightness).

The various settings can easily be entered from a PC and can be changed whenever necessary, and from any location. The changes are sent to the GPRS-equipped Comlight unit, which then automatically transmits the update to all the lights along the stretch of road or at the site.

<table>
<thead>
<tr>
<th>GPRS adjustable parameter settings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of light points forward to be triggered from detecting unit in both fast and slow detection channel</td>
</tr>
<tr>
<td>Light level when traffic is detected</td>
</tr>
<tr>
<td>Light level when no traffic is detected</td>
</tr>
<tr>
<td>Settings for rush-hour traffic, e.g. temporary high level intensity at pre-set times of day, evening or night</td>
</tr>
<tr>
<td>Crossroad or junction handling</td>
</tr>
<tr>
<td>Time to keep high light level when traffic is detected</td>
</tr>
</tbody>
</table>

**Comlight Luminizer Central Management System**

LUMINIZER is the Comlight Central Management System, and is fully integrated with Comlight Eagle Eye and Google Maps. It can be utilised for remote configuration at commissioning only, or it can store the installation status and history in the database. The software system can handle all the information obtained outdoors and will function as the streetlight organizer. It offers web interface to the public for lamp failure reporting and full control of the streetlight installation, from commissioning to daily operations and planned maintenance activities. This is an easy way to stay in control of the total streetlight installation and reduce total cost of ownership.

**Luminizer CMS**

- Expert engine to assist streetlight monitoring
- Integrated with Google Maps
- Remote connection over TCP/IP (GPRS)
- SQL database and fully scalable system
- Standard web technology and SOAP/XML for integration to other 3rd party systems
Energy Savings

Some variables can affect how much energy it is possible to save, such as the amount of traffic on the roads. The financial and documented savings for smart street lighting can be calculated in advance for every installation, taking into account traffic congestion, energy prices and installed effect on the luminaire. Comlight in co-operation with The Norwegian Road Authorities, Eastern region, has verified the effect of activity based street lighting by Comlight. The measurements showed an energy saving of 45% within a 1-year period.

Distribution

Today Comlight is operating throughout Europe and the system is represented in over a few thousands light points. Comlight is constantly expanding through its distribution partners. The company’s target market is all street lighting outside of city centers and the most heavily trafficked highways. The system is perfect for residential areas, mid-sized and smaller streets, parks and big industrial areas, but there is great potential for parking lots as well. Comlight sells to commercial distributors and is continuously working to find distribution partners that match its environmental values and future plans.
Aspects in the determination of measurement uncertainty in the evaluation of light installations

Peter Blattner

Abstract

Lighting installations must comply with quality criteria. The lighting levels and quality parameters are defined by relevant standards and guidelines. When comparing the specification values with the measured values the measurement uncertainty plays an important role. Only on the basis of the measurement uncertainty a statement about the quality of the measurement can be made, allowing ultimately a judgement whether the requirements are met or not. The determination of measurement uncertainty is complex and expensive. In practice there are usually simplified procedures used for the evaluation. The new European Standards for road lighting and the new international measurement standard for LED lamps and luminaires will help the user to understand and evaluate measurement uncertainties.

Introduction

Light plays a central role in science, technology and culture. Advances in lighting and solar energy are considered decisive for the future sustainable development. Good lighting brings safety and a better quality of life for all. It is the job of the photometry to quantify the properties of light. For this purpose, a number of measurement quantities are defined. The total amount of emitted light (luminous flux, unit lumen) is typically declared on the packaging of lamps. International standards specify the illuminance levels (luminous flux per area, unit Lux) in a football stadium or the luminance of a road (unit candela per square meter).

Photometric measurement quantities and measuring instruments

In photometry typically illuminance meters, luminance meters and imaging luminance measurement devices are used to determine the relevant quantities. A basic characteristic of these photometric instruments is that they measure the optical radiation spatially and spectrally weighted. For example, an illuminance meter measures the amount of light (luminous flux) per surface area which falls onto a surface. If the radiation falls oblique on the detector less light is collected. The sensitivity of an ideal illuminance meter therefore has to change with the cosine of the angle of incidence. If it deviates from the cosine function measurement errors arise. Depending on the geometry these errors can be significant.
Critical examples are the determination of the vertical illuminance on a pedestrian crossing when the light hits the surface of the detector on a grazing incidence.

**Figure 1 a)**
Illuminance is defined as luminous flux per surface area

**Figure 1 b)**
If the surface is tilted the apparent collecting surface varies with the cosine of the tilting angle

**Figure 1 c)**
The angular responsivity of an illuminance meter needs to follow the cosine law

Similar considerations can be made for the spectral weighting. All photometric devices need to match their spectral responsivity to the standardized spectral luminous efficiency function $V(\lambda)$, see Figure 2. Due to practical reasons this match can never be perfect and measurement errors will occur.

If the spectral sensitivity of the detector and the spectral distribution of the light source are known this error can be reduced or corrected for. However as these spectral functions are known with a limited accuracy some uncertainties on the measurement will remain. The goal of a reliable measurement is to avoid and correct errors and to determine the (remaining) measurement uncertainty.
Measurement uncertainty

When comparing the specification values with the measured values the measurement uncertainty plays an important role. Only on the basis of the measurement uncertainty a statement about the quality of the measurement can be made, allowing ultimately a judgement whether the requirements are met to a lighting system or not. The new European Standard on road lighting EN 13201-4:2015 [7] requires that all comparison of measured results with standard requirements or design expectations shall be carried out considering the expanded measurement uncertainty of the measure:

- for parameters that require a value greater or equal to a given level, the lower limit of the coverage interval of the expanded measurement uncertainty shall be greater or equal to the given level;
- for parameters that require a value lower or equal to a given level, the upper limit of the coverage interval of the expanded measurement interval shall be lower or equal to the given level.

Thus a correct evaluation of uncertainty is important. In the worst case a wrong judgement is done, i.e. a lighting installation is rejected even if it should accepted – or vice versa. The approach defined by the new European Standard on road lighting puts the risk of wrong assessment on the “producer”. The probability that an installation is reject due to the wrong judgement is much higher than it is wrongly accepted.

Even for simple measurement tasks, like the measurement of the illuminance distribution on a street, the accurate determination of the measurement uncertainty is complex and time consuming. General guidance on the determination of the measurement uncertainty is given in the “GUM” (Guide to the
expression of uncertainty in measurement [1]). The determination involves the following steps:

- Identification of the influence parameters and their relation to the output quantity (expressed typically through a mathematical equation),
- Determination of the sensitivity of the influence parameters to the output parameter,
- Quantification of the influence parameters and their uncertainties,
- Calculation of the uncertainty of the output parameters by combining the different contributions of the influence parameters.

In many cases only little information on the acceptable quality is available or the effort to determine the needed parameters is too high. The estimated uncertainty might therefore be quite large. However in all cases a basic principle of metrology is valid: The more information about the measurement process is available, the more accurately measurement errors can be corrected, resulting in smaller measurement uncertainties. In practice measurement uncertainty can be considered as having three groups of components:

- Those related to the calibration of the photometer,
- Those due to the difference between the calibration conditions and the measurement conditions,
- Those related to an uncertainty in the definition of the measurement quantity.

### Calibration of photometers

The calibration of illuminance meters is typically done at National Metrology Institute (NIST, NPL, PTB, METAS,…) or at an accredited calibration laboratory. These laboratories use reference illuminance meters traceable to the national realization of the photometric units. At an international level these realizations are regularly compared to ensure consistency among the different countries.

When calibrating illuminance meters a number of contributions have to be considered, including position accuracy, spectral match, temperature sensitivity, straylight, linearity, etc. and the uncertainty of the reference illuminance meter. Guidance on the determination of measurement uncertainty in photometry is given by the CIE publication 198 [2].

In this context the calibration of measurement devices means the comparison to a reference device at well-specified conditions. As an example, illuminance meters are calibrated at a room temperature of 25°C using an incandescent light source with a correlated colour temperature of 2,856 K (hence CIE Standard Illuminant A) at well-defined geometry (far-field condition and at perpendicular incidence).

If the illuminance meter is used to measure the illuminance distribution on a road, the measurement conditions are completely different to the condition in
the laboratory: The temperature may be well below 25 °C, today usually LED luminaires are used having different spectral distribution as an incandescent light source, and the illumination angle will be different from perpendicular incidence.

For the determination of the measurement uncertainty the difference between the calibration conditions and the measurement conditions have to be considered. The influence of the ambient temperature can be found quite easily. The determination of the influence of the geometry and the spectral distribution of the light sources is more tricky: Ideally the spectral distribution of the light source and the spectral sensitivity of the detector are known. In this case the error can be quantified, corrected and the measurement uncertainty estimated.

Similar is true for the angular error: If the angular sensitivity of the measurement devices and the illumination geometry are known, the error due to a cosine mismatch can be corrected and the remaining measurement uncertainty can be determined. The correction factors will depend on the quality of the devices. A high precision instrument will better match the cosine and $V(\lambda)$ functions and thus the correction factor will be closer to one.

**Quality indices**

The International Commission on Illumination (CIE) has defined in its standard CIE S023 a set of quality indices ($f_1$, $f_2$, $f_3$, ...) applicable for photometric measurement devices [3]. The standard defines quality indices characterizing the performance of photometers in general lighting measurement situations for the relevant parameters. It is important to note that these indices do not directly represent the error of the device or the measurement uncertainty. Nevertheless, it is generally true that instruments with smaller $f_X$-values allow, in most cases, for smaller measurement uncertainties than instruments with larger values.

**Spectral sensitivity**

Photometric measurement devices use specially designed filters to match their spectral sensitivity to the standardized spectral luminous efficiency function of the human eye $V(\lambda)$. Due to technological limitation and uncertainties related to the determination of the spectral responsivity these matches can’t be perfect. The quality of the match is quantifiable using the quality index for spectral match $f'_i$. This parameter is defined by the difference between the normalized spectral responsivity $s^*_\text{rel}(\lambda)$ and the standardized spectral luminous efficiency function $V(\lambda)$:

$$f'_i = k \int |s^*_\text{rel}(\lambda) - V(\lambda)| \, d\lambda$$

where $k$ is a scaling factor.
The equation above includes the absolute value function of the difference between the actual and the target function, thus positive and negative deviations are summed up.

High precision photometers with very fine spectral match have a $f_1'$ below 1.5%, handheld devices typically below 6%. Unfortunately many low cost photometers don’t specify the quality of the spectral match and no judgement of quality of the measurement is possible with these devices.

**Angular sensitivity**

As previously described illuminance meters need to evaluate oblique incident light according to the cosine of the incident angle $\varepsilon$. The quality index for cosine match $f_2$ of a rotation symmetrical detector (i.e. its responsivity doesn’t depend on the azimuth angle $\varphi$) is given by

$$f_2 = \int |Y^*(\varepsilon) - \cos \varepsilon | f(\varepsilon) \, d\varepsilon$$

where $Y^*(\varepsilon)$ is the normalized angular sensitivity and $f(\varepsilon)$ an angular weighting function. As in the case of $f_1'$ the absolute value of the difference between the measured and the target function is summed up.

**Measurement uncertainty of the quality indices $f_1'$**

The determination of the quality indices is subject to some uncertainties which will limit the realization of high precision instruments. One point to consider is that the absolute value function used in the definition (i.e. Eq. 1 and 2) is a non-linear function around the zero point.

It is therefore not possible to apply the GUM standard evaluation procedure but Monte-Carlo simulations are necessary: Based on the measurement uncertainty of the spectral responsivity a large number of “fictive” spectral responsivity curves are numerically generated and the $f_1'$ values of these “fictive” devices is calculated, resulting in a statistical distribution of $f_1'$. This distribution can be described by a best estimate (average value) and standard deviation of the quality index $f_1'$. Further guidance to the Monte-Carlo method is given in GUM supplement 1 [6].

For high quality photometers a non intuitive effect can be observed: The best estimate of the quality index depends not only on the spectral responsivity but also on the uncertainty of the spectral responsivity measurement. Thus the realization of high precision photometers requires highly accurate measurements of the spectral responsivity. This unusual behaviour can be best illustrated is shown in Figure 4.
The closer the match between the spectral responsivity of the detector and the \( V(\lambda) \) function the higher is the influence of the uncertainty of the spectral responsivity on \( f_1' \). Even if there is a presumed perfect match of the detector (i.e. \( f_1' \) evaluated according equation 1 would be zero) considering the measurement uncertainty of the spectral responsivity determination will result in an estimated \( f_1' \) different from zero.
Estimation of the measurement uncertainty on the value of \( f_1' \)

As previously mentioned the quality indices can’t be directly used for the determination of the measurement uncertainty of a specific measurement situation. However they give some indication on the possible errors in general situations. METAS has evaluated the spectral sensitivity of a large number of photometers and calculated the spectral correction factors for a large number of “classical” light sources (incandescent lamps, fluorescent lamps, sodium high pressure lamps, …) and white LED light source (see also [8]). Figure 5 reports the spectral correction factor as a function of the quality index \( f_1' \) for a) classical light sources and b) RGB-LED based white light sources. It is well true that for highly accurate instruments having low \( f_1' \) the correction factors are close to one. The results of Figure 5 can be used to estimate the measurement uncertainty due to spectral mismatch even if the spectral distribution of the light source is not known precisely: For classical light sources the error lies between \( \pm \frac{1}{2} f_1' \) as indicated by the two black lines in the figure. For white LED sources (with RGB technology) this error typically doubles.

\[ \begin{align*}
\text{Figure 5} & \\
\text{Correction factor of different light sources as a function of the quality index } f_1', \text{ of different photometers. The better the photometer, the smaller the } f_1' \text{ value resulting in a correction factor close to one.} \\
\text{Figure 5a)} & \ \\
\text{Classical white light sources} & \\
\text{Figure 5b)} & \ \\
\text{LED white light sources (RGB technology)} &
\end{align*} \]
Much higher errors will occur if coloured light sources have to be measured; in particular blue or red, and no general statement is possible even for high precision photometers.

**Uncertainty caused by the measurement process**

In addition to the above-mentioned uncertainties due to the measuring device, uncertainties caused by the measurement process have to be considered. Usually the relevant lighting application standards define the measurement conditions (i.e., measurement grid). In addition, requirements are given to the positional accuracy of the measurement grid points. For example, the European road lighting Standard EN 13201-4 specifies that the entrance aperture of the photometer should be located not more than 200 mm above the road surface. Larger differences between two measurements are possible even if the standard is fulfilled:

If the illuminance is measured directly below a point light source that is located 4 m above the measurement grid point the illuminance varies by 10% between the road surface and 200 mm above the surface. In addition, the luminance may vary significantly in function of the lateral position and the observation angle. Examples are shown in Figure 6 with variations of 5% per 10 cm lateral change and 10% per 0.5° change in the observation angle.

![Figure 6](image_url)

*Measured road surface luminance as a function of a) the lateral position b) observation angle*
Comparison of measurement with the target values

The measurement values are typically used for verifying the compliance of a lighting installation with standard requirements and/or with design expectations. Due to economic and structural conditions there are usually only a few degrees of freedom in the design of lighting installation. The photometric data of luminaires play a major role on the design of the installation. These data are typically obtained by measuring the luminous intensity distributions of one representative luminaire on a goniophotometer. Depending on the measurement equipment the uncertainty of the photometric data of the luminaire varies largely, as outlined in the new standard for LED measurement [4,5]. Comparing measurement values of a lighting installation to the target values, additional effects have to be considered (production tolerances of the luminaires, ageing properties, degree of pollution, temperature influence, etc.). Overall uncertainties of 10 % to 30 % are quite common and should be considered when assessing lighting installation.

Literature

[7] EN 13201-4 Road lighting – Part 4: Methods of measuring lighting
Intelligent ECG technology controls light according to individual demand

Ralf Müller

Electronic control gears (ECG) have become indispensable for street lighting since their introduction around 20 years ago. Initially, ECG were used in traditional luminaires as an alternative to the usually applied conventional control gear (CCG), primarily in order to offer the user the opportunity of reducing energy costs (lower power consumption of the control gear, power-reduced operation through dimming) and/or of expanding service intervals through the optimized operation of the lamp at the ECG (longer lamp lifespan due to a lower decline in luminous flux, flicker-free operation).

For technical reasons, it is necessary to use an ECG for modern LED luminaires, so that the LEDs are supplied with constant current and thus achieve the desired lifespans. Therefore, operators of outdoor luminaires will in future have to deal with ECG issues more often than this was usually necessary in the past. However, the application of ECG also offers various options of using them individually, as necessary or as required, in order to fully tap further energy-saving potentials.

Some of these options will be outlined in this article.

**Half-night switch – StepDIM**

One of the first dimming options that came with electronic control gear for outdoor use was the adoption of the half-night switch, which in part had already been used for a long time for CCG with 2-step dimming and which often needed additional components or a relay to convert the switching signal into a 1...10 V signal.

![Half-night switch operation](image-url)
With electronic control gear, these additional elements are not needed. For the half-night switch, 2 phases of the mains are connected directly to the ECG and by switching the second phase off, the dimming operation starts.

For 100-% operation, the second phase will be simply switched on, which results in the system’s operation over the night as shown in figure 1.

“Autonomous dimming – AstroDIM”

This principle was then advanced to “autonomous dimming” – an operating mode which is called “AstroDIM” when used in OSRAM ECG. This became necessary for system operators that did not have a second phase available in the mains but still wanted to be able to use the dimming option. By recording the luminaire’s on and off times (which are specified by the luminaire operator), intelligent controllers in the ECG calculate an average value of the luminaire’s operating time.

Configurable dimming times and dimming levels result in a specific operating time for 100-% operation and for the time during which the ECG is operated in power-reduced mode.

If requested, the power-reduced operation can be designed as a two-stage process (as shown in figure 2) and can be adjusted to individual requirements.

![Figure 2: Power-reduced operation in the AstroDIM mode](image)

Because the ECG re-calculates the average operating time again and again, it is capable of displaying the night times over the year in the dimming profile (short nights in summer and long nights in winter).

In the ECG, the DIM values (e.g. 60 % of the power) and the duration of the power-reduced operation (e.g. 6 hours per night) in the AstroDIM mode are factory-preset. If requested, these settings can be newly parameterized before integrating the ECG into the luminaire.
Intelligent ECG technology controls light according to individual demand.

Length of the night

<table>
<thead>
<tr>
<th>Location time (h)</th>
<th>Dim level %</th>
<th>Mains</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OFF</td>
<td>OFF</td>
</tr>
<tr>
<td></td>
<td>OFF</td>
<td>OFF</td>
</tr>
<tr>
<td></td>
<td>OFF</td>
<td>OFF</td>
</tr>
<tr>
<td>ON</td>
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<tr>
<td>ON</td>
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<td>ON</td>
</tr>
<tr>
<td>ON</td>
<td>ON</td>
<td>ON</td>
</tr>
</tbody>
</table>

Operating time

Figure 3  Adjustment of the AstroDIM module over the year
ECG in combination with light management systems

Another important step in terms of individual outdoor lighting is the transfer of light management systems (LMS) from indoors to outdoors. Some manufacturers, however, offer individual solutions which do not function with other components or systems from other manufacturers. For outdoor applications, larger LMS manufacturers such as Philips or OSRAM rely on the DALI® standard:

If operators decide to use such a system, they are enabled to control each light point individually via software. This usually happens in a control center, from which the commands are either sent to the luminaires by radio or via cable connection (e.g. through the existing phasing line via power line signal). An interconnected DALI® controller then converts the command into a DALI® signal and forwards it to the DALI®-compliant ECG, so that it carries out the command and/or delivers the requested information.
The most important commands/pieces of information which can be sent to (or via) and received by the ECG:

<table>
<thead>
<tr>
<th>Command/Piece of Information</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimming/power reduction</td>
<td>Individual setting of the DIM levels possible at any time</td>
</tr>
<tr>
<td>On/off switch</td>
<td>Individual switching (on/off) of the luminaire possible at any time</td>
</tr>
<tr>
<td>Boosting</td>
<td>Individual power-up during special situations (e.g. events, accidents at large traffic junctions) if necessary</td>
</tr>
<tr>
<td>ECG status information</td>
<td>Current operating status report of the control gear and the light source</td>
</tr>
<tr>
<td>Current and power monitoring</td>
<td>Recall of the current voltage and current consumption to optimize the service intervals and troubleshooting via the LMS component</td>
</tr>
<tr>
<td>Operating time</td>
<td>Recall of the operating times of light sources and ECG to optimize service intervals</td>
</tr>
</tbody>
</table>

Table 1  List of the most important DALI® commands/pieces of information

“Constant light” – constant lumen output

The “constant light” option was yet another step for saving energy with the introduction of LED technology. With this application, the decline in luminous flux of the LED is compensated by readjusting the power. The luminaire – i.e. the LED module – is dimmed right from the first start-up. Over the course of the operating years, the LEDs are boosted in order to counteract the decline in luminous flux. This is done to achieve three objectives:

- Lifespan extension of the LED modules
- Constant light on the road
- Saving energy, because at the start of the operation, the luminaire is operated in dimmed state (e.g. at 70%) and is powered up to 100-% operation only over the course of the operating time

Figure 6
Constant lumen output – power control via operating time
This setting in the ECG is possible if the luminaire flux characteristics of the applied LED component are roughly known and if it is supported by the ECG. With this setting, the power increase has to be defined based on the operating duration.

**Figure 7**
Constant lumen output – decline in luminous flux and readjustment via operating time

**Figure 8**
Power increases after specific operating hours at constant lumen output
ECG in combination with sensors

With the help of sensors (light sensor or presence detection through a motion sensor), additional control features in outdoor lighting can be generated. This might be of interest in applications where light in the night is needed for security reasons but where user traffic is too low to make constant, maximum-level lighting economical. Appropriate application examples for ECG/sensor combination, e.g.: parking areas, parking garages, bicycle lanes or footpaths.

Possible set-ups with sensors:

**Figure 9**  
Luminaire with sensor;  
ECG connected with control line via StepDIM mode

**Figure 10**  
Luminaire with sensor and radio communication;  
ECG connected via DALI® control line
A motion sensor, wired to the luminaires through a connection (e.g. DALI® control line, see figure 11), is installed at a suitable location. In case an object or a person is detected by the sensor, a signal is triggered which is transmitted to the ECG through the DALI® interface, or (as shown in figure 9) via the control line as the second phase in the StepDIM mode. Depending on the desired setting, the switched-off or dimmed luminaires are then powered up to 100 % and, after some time, powered down to their initial level.

**Conclusion**

Depending on the application, engineers and operators of lighting systems have to deal with specific requirements. With the help of various operating modes, modern ECG technology supports the operators in designing the systems economically and saving energy costs without jeopardizing road safety.
Mesopic research – foundations and new results

Peter Zsolt Bodrogi

1 Motivation, questions

Mesopic vision or twilight vision takes place in the luminance range 0.001 cd/m² and about 5 cd/m². In this range, both the rods and the cones of the retina are active. Under certain circumstances and for the case of several lighting situations, the range below 0.01 cd/m² is already scotopic because the cones, especially the blue sensitive so-called “S-cones”, are not active. Anyway, latter range is not relevant for street lighting applications. Concerning the upper limit of the mesopic range, for certain visual objects and observation conditions, it may extend up to 60 cd/m².

Technologically and from the lighting engineer’s point of view, knowledge on the mesopic range is required according to the following reasons. ME-class streets (according to DIN EN 13201) have a luminance between 0.3 cd/m² and 2.0 cd/m² and they are illuminated by different light sources like high-pressure sodium lamps, mercury-vapour lamps, metal-halide lamps (e.g. Cosmopolis lamps) and white LEDs. Their correlated colour temperatures range usually between 2,800 K and 6,500 K. The spectral power distributions of these types of lamps are very different. They emit different amounts of radiation in the blue and red wavelength ranges. In this context, the following two questions arise in the context of the recent trend of replacing sodium lamps and mercury-vapour lamps by white LED lamps:

- Does the road user perceive the street illuminated by street lighting of different type and different spectral power distribution but of the same average luminance equally bright or are there significant perceived brightness differences among the different types at the same luminance level?
- What lamp types of street lighting with what kinds of spectral power distributions are acceptable and visually comfortable for the residents?

2 Human visual system, visual tasks

There are four receptor types on the retina to yields signals for further visual information processing in the human visual brain. The three cone types, so-called “L-, M- and S-cones” are active in the luminance range of both daytime and mesopic (twilight) vision. They are spectrally sensitive in the long (L–), middle (M–) and short (S–) wavelength range of the whole range of visible radiation. The spectral sensitivity of the rods which are active in night-time vision and also in the mesopic range peaks at 507 nm, see Figure 1:
Figure 1  Spectral sensitivity of the L-, M-, and S-cones, the $V(\lambda)$ function (the basis of standard photometry) and the $V'(\lambda)$ function (spectral sensitivity of the rods responsible for night-time vision)  [Source: TU Darmstadt]

The angular distribution of cones and rods on the retina is depicted in Figure 2:

Figure 2  Angular distribution of cones and rods on the retina, re-drawn after [1]

As can be seen from Figure 2, there are only cones and no rods in the central region of about 1.25° within the so-called “fovea”. Going from the fovea toward the periphery of the retina, cone density diminishes drastically but the number of rods increases. Photoreceptor distributions influence the efficiency of visual task performance – depending on the type of visual task. Visual tasks include the visual assessment of brightness, visual search, object detection, and object recognition (visual acuity) [2]. Two important tasks, brightness assessment and object recognition will be dealt with in detail below.
It should be noted that, within the mesopic range, visual perception characteristics are very variable. Mesopic visual performance depends on the following parameters:

- the type of visual task, e.g. brightness assessment or object recognition (visual acuity),
- luminance level, e.g. 0.1 cd/m² or 1.0 cd/m²,
- chromaticity (relative spectral power distribution) of street lighting, e.g. a yellowish high-pressure sodium lamp or a cold white LED street lamp and
- the size and angular position of the object or part of a scene in the field of view of the observer.

2.1 Brightness assessment

Brightness assessment is usually a longer process that usually takes more than 3 seconds, see Figure 3:

![Figure 3](image)

In the example of Figure 3, the subject observes and assesses the brightness of the whole scene. The central part of the viewing field around the fixation point (2°) is depicted by a red dot in Figure 3. The red circle represents the 10° diameter part of the scene around the fixation point. The red arrow points toward a typical hazard point where a pedestrian might suddenly step out.

To assess the brightness of the scene, the observer scans the whole field of view and evaluates the amount of light reflected from the objects visually (see Figure 3). Scene brightness perception influences the feeling of personal safety as well as the aesthetic impression of the observed street scene.
2.2 Object recognition (visual acuity)

The recognition of an object is based on the perception of the fine spatial details of the object. The observer needs a good resolution at that part of the retina where the object and its details are imaged. The perceived spatial pattern is compared with known patterns stored in the long-term memory of the subject and the object is recognized. To recognize an object (e.g., a letter), the central 2° field of view of highest resolution (visual acuity, see Figure 2 and the red dot in Figure 3) migrates – as a consequence of dedicated eye movements – towards the object to be recognized and the spatial pattern of the object (e.g., a letter) is being scanned.

3 Mesopic brightness perception of different lamp types [3]

In the experiment, observers had to match the mesopic perceived brightness of two adjacent fields of different chromaticity by adjusting the luminance of one of the fields. Observers sat in front of a double-chamber light booth at a distance of 1 m in a dark room in which the only light source was the bipartite viewing field of the booth, see Figure 4.

The reference light source was installed in the right chamber and three mesopic luminance levels were used, 0.1, 0.5 and 1.5 cd/m². Test light sources were installed in the left chamber. After a mesopic adaptation period of 20 minutes, observers had to adjust the luminance of the test field (see Figure 4) until the brightness of the two fields matched visually. 18 observers carried out 3 repetitions per observer. Table 1 summarizes the properties of the reference and test light sources. The mercury-vapour lamp (HQL) was the reference lamp for the first group of test light sources (street lamps: CPO, MH, NAV) while for the second group (car headlamps: XE, LED) the H7 (halogen) was used as reference light source.
Table 1  Reference (R) and test (T) light sources. Correlated colour temperature $T_C$ in K units. LS: light source. $R_a$: general colour rendering index

<table>
<thead>
<tr>
<th>LS</th>
<th>Description of the lamp</th>
<th>R/T</th>
<th>Type</th>
<th>$x$</th>
<th>$y$</th>
<th>$T_C$</th>
<th>$R_a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HQL</td>
<td>Mercury-vapour</td>
<td>R</td>
<td>HQL-MBF-U</td>
<td>0.390</td>
<td>0.380</td>
<td>3,560</td>
<td>54</td>
</tr>
<tr>
<td>CPO</td>
<td>Cosmopolis discharge</td>
<td>T</td>
<td>CPO-T</td>
<td>0.483</td>
<td>0.412</td>
<td>2,440</td>
<td>60</td>
</tr>
<tr>
<td>MH</td>
<td>Metal halide</td>
<td>T</td>
<td>CDO-TT</td>
<td>0.426</td>
<td>0.446</td>
<td>3,510</td>
<td>67</td>
</tr>
<tr>
<td>NAV</td>
<td>High-pressure sodium</td>
<td>T</td>
<td>SON-T</td>
<td>0.553</td>
<td>0.421</td>
<td>1,860</td>
<td>-6</td>
</tr>
<tr>
<td>H7</td>
<td>H7 halogen</td>
<td>R</td>
<td>H7</td>
<td>0.430</td>
<td>0.408</td>
<td>3,160</td>
<td>98</td>
</tr>
<tr>
<td>XE</td>
<td>Xenon</td>
<td>T</td>
<td>HID-Xe</td>
<td>0.386</td>
<td>0.392</td>
<td>3,960</td>
<td>70</td>
</tr>
<tr>
<td>LED</td>
<td>White LED</td>
<td>T</td>
<td>LED</td>
<td>0.303</td>
<td>0.284</td>
<td>7,860</td>
<td>82</td>
</tr>
</tbody>
</table>

The resulting brightness matching dataset consisted of ratios of luminance values $R = (L_{test}/L_{ref})$ obtained for visually matching mesopic brightness for all test-reference light source pairs, mesopic luminance levels ($L_{ref} = 0.1; 0.5$ and $1.5 \text{ cd/m}^2$), observers and repetitions. These $R$-values were averaged across all observers and repetitions. Figure 5 shows the result:

![Figure 5](image)

Figure 5  Mean ratios of luminance values $R = (L_{test}/L_{ref})$ at visually matching mesopic brightness for all test-reference light source pairs and mesopic luminance levels ($L_{ref} = 0.1; 0.5$ and $1.5 \text{ cd/m}^2$). Mean ratios for all observers and repetitions. 95% confidence intervals are also shown. If we suppose that the quantity luminance can predict mesopic brightness perception with good accuracy then all $R$-values should equal 1.000 (which is obviously not true). This condition is indicated by the horizontal black line  

[Source: TU Darmstadt]
The following can be seen from Figure 5:

- Expressed in luminance (cd/m²) units, 80–85% of white LED light is enough to evoke the same brightness perception as with the yellowish H7 reference lamp (depending on mesopic luminance level),
- Observers need 5%–50% more luminance from the light of the test lamps CPO, NAV und MH compared to the mercury-vapour lamp in order to evoke the same brightness impression. This effect is especially strong for the case of the yellowish NAV lamp at the 0.1 cd/m² level.

As a conclusion, it should be noted that the mesopic brightness perception of e.g. an extended street area cannot be predicted by using luminance (standard photopic luminance in cd/m² units) as a descriptor quantity. Using a lamp with a higher mesopic brightness impression (e.g. a cold white LED lamp), not only perceived brightness but also related measures like feeling of safety, aesthetic impression and visual search performance can be improved.

4 Mesopic object recognition, visual acuity [4]

As mentioned above, visual acuity corresponds to the ability to recognize fine object details with high luminance contrast. An important question is if visual acuity in the mesopic range depends on the chromaticity of the light source (e.g. a cold white LED or a yellowish high-pressure sodium lamp) used to illuminate a scene with different objects to be recognized (e.g. traffic signs, letters or faces of pedestrians). A dedicated visual experiment [4] will be described below. In this experiment [4], observers had to recognize letters of fixed resolution and size (fixed visual acuity) and the contrast of the letters was varied. This experimental task corresponds to the visual tasks in typical street lighting situations. This is not a classic visual acuity test but a so-called “letter contrast acuity test”.

Figure 6
Illustration of the Pelli Robson test chart
The so-called “Pelli Robson chart” was used as visual task at a viewing distance of 3 meters, see Figure 6. The letter size equalled 48.5 mm (about 1°). This corresponds to an object size of 0.8 m at a viewing distance of 50 meters. The chart consists of letters in groups of three and with decreasing contrast. During the visual experiment, a group was considered as recognized when at least two of three letters were named correctly. The luminance of the test chart was varied between 0.1 cd/m² and 2 cd/m² in this study [4]. Concerning the light sources, a tungsten halogen lamp (H7), a neutral white LED with 4,693 K often used in street lighting, a HID (D2S) car headlamp, and two modified HID lamps were selected, see Table 2. Fifteen subjects participated in the experiment.

<table>
<thead>
<tr>
<th>Light Source</th>
<th>$x$</th>
<th>$y$</th>
<th>$T_c$ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tungsten</td>
<td>0.4447</td>
<td>0.4071</td>
<td>2,894</td>
</tr>
<tr>
<td>HID 1</td>
<td>0.3888</td>
<td>0.3968</td>
<td>3,928</td>
</tr>
<tr>
<td>HID 2</td>
<td>0.3663</td>
<td>0.3751</td>
<td>4,392</td>
</tr>
<tr>
<td>HID 3</td>
<td>0.3578</td>
<td>0.3506</td>
<td>4,523</td>
</tr>
<tr>
<td>LED</td>
<td>0.3544</td>
<td>0.3603</td>
<td>4,693</td>
</tr>
</tbody>
</table>

Table 2  | Colorimetric properties of the light sources measured on the Pelli Robson chart surface [4]

Contrasts on the Pelli Robson test chart were measured by a luminance camera and contrast values were calculated for each letter. Results showed an increasing letter contrast acuity with increasing chart luminance, see Figure 7:

Figure 7  | Mean values and standard deviations of the number of the last recognized letter group for the five lamp types listed in Table 2
As can be seen from Figure 7, the type (chromaticity) of the light source (see Table 2) does not influence letter contrast acuity significantly. It can be stated that – at least under the viewing conditions used in this study – letter contrast acuity correlates well with (standard photopic) luminance contrast – independent of illuminant type (chromaticity). The reason is that, during foveal observation, there are no rods involved in the recognition task (and also no S-cones) so that the $V(\lambda)$ spectral sensitivity function is valid (compare with Figures 1 and 2).

5 Summary and outlook

For the brightness assessment of large visual fields (e.g. of a whole street scene), the chromaticity of the light source illuminating the street (e.g. a cold white LED or a more yellowish sodium lamp) is very important. The quantity of (standard, photopic) luminance cannot describe mesopic brightness perception. The scene under a street lamp with a cold white tone appears brighter in the mesopic range (e.g. for typical luminance levels between 0.1 and 2.0 cd/m$^2$) than under a street lamp with a yellowish tone. For object recognition, visual performance turned out to be independent of light source chromaticity so that photopic luminance can be used.

Today, the most important question of light source designers for street lighting and road lighting is: „Would it be reasonable to decrease the illuminance level of street lighting below the value required by the standard if a cold white light source (e.g. a cold white LED) is used instead of e.g. a yellowish high-pressure sodium lamp?” The answer is clearly “No” because, for street lighting and vehicle lighting, mesopic object recognition (see Figure 7) and mesopic brightness perception (see Figure 5) are equally relevant.

Literature


Management Information System for street lighting
Documentation, maintenance planning and data analysis

Armin Mühlberger

Street lighting improves the safety of traffic and increases the attractiveness of roads and public places. Light brings life to a town or countryside. It makes us feel secure. But how does it look like behind the scenes?

Figure 1 The illuminator’s tasks
Years ago, the operation of street lighting was a clear and manageable job. But due to the technical progress, street lighting became more complex and extensive. Now you need to have a large technical know-how. The options and requirements have changed. The user and owner of street lighting are faced with competition and economization. Often street lighting will be perceived when it disturbs or it is broken. Light seems to be naturally. But it is often very time-consuming and expensive to supply our streets with light. These efforts are kept behind the curtains. There are widespread and extensive processes in the background. In Figure 1 you will find the operations of an employee responsible for street lighting.

**Documentation**

The documentation of individual components used for a single site is often difficult, tough and time-consuming. But it is the basis for all future decisions. If you don’t have enough and reliable data you are not able to come to a substantiated agreement, when time is short.

This is the reason for many gut decisions with unsureness, unsteadiness and risks. You need to have a large and comprehensive documentation to avoid this. In times of economization and less tax revenue the operation of lighting systems will be more difficult. Without an accurate documentation you are not able to find out, where you need to invest or where you can save investments. Today you still find the inventory of street lighting either as a hardcopy or there is no documentation. Quite often these data are incomplete and don’t match with the reality. Sometimes there is an existing documentation but on different systems. Due to less time, data changes are not transcribed to all systems. The result is that these data collected don’t correspond with the real inventory.

To avoid this mismatch a permanent actual electronic documentation is needed. An information system will support you with:

- a secure an economical service of street lighting
- an immediate elimination of faults
- a rational and projectable servicing
- a proof document of services, testing and keeping dates
- analytical statistics of increasing faults to plan investments for the next year
- cost savings

If you want to implement a management information system for your equipment you have to find out, if there already runs a system in your company which could be used for documentation of street lighting? Which are your requirements? How large should be the range of data to be documented?

There are many questions to be clarified. The first step will be to find out the amount of data you want to keep record. Below you find an example which can be altered according to your needs:
### Light point

<table>
<thead>
<tr>
<th><strong>category</strong></th>
<th><strong>content</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>mast no.</strong></td>
<td>specification of cadastral land register – city map</td>
</tr>
<tr>
<td><strong>location level</strong></td>
<td>site characterisation</td>
</tr>
<tr>
<td><strong>region</strong></td>
<td>specification of cadastral land register – city map</td>
</tr>
<tr>
<td><strong>road</strong></td>
<td>specification of cadastral land register – city map</td>
</tr>
<tr>
<td><strong>type of road</strong></td>
<td>federal highway, national highway, main road, motor road, cycle way,</td>
</tr>
<tr>
<td></td>
<td>residential street</td>
</tr>
<tr>
<td><strong>speed limit</strong></td>
<td>according to road traffic regulations</td>
</tr>
<tr>
<td><strong>status</strong></td>
<td>operating, mantled, out of order</td>
</tr>
<tr>
<td><strong>type</strong></td>
<td>street lighting, cross walk, subway, cycle track, tunnel, parkway,</td>
</tr>
<tr>
<td></td>
<td>spotlighting, stopping point, etc.</td>
</tr>
<tr>
<td><strong>type of light point</strong></td>
<td>power, gas</td>
</tr>
<tr>
<td><strong>coordinates</strong></td>
<td>Easting, Northing</td>
</tr>
<tr>
<td><strong>material mast</strong></td>
<td>steel, aluminium, plastic, wood, cement, other …</td>
</tr>
<tr>
<td><strong>material collar</strong></td>
<td>steel, plastic, bitumen, other …</td>
</tr>
<tr>
<td><strong>coating mast</strong></td>
<td>Zinc coating, plastic, painting, other, zinc coat + painting</td>
</tr>
<tr>
<td><strong>Year of construction mast</strong></td>
<td>Estimated year of construction</td>
</tr>
<tr>
<td><strong>Mounting height</strong></td>
<td>estimated or metered</td>
</tr>
<tr>
<td><strong>type of luminaire</strong></td>
<td>post top lamp, mushroom luminaire, bell, lother</td>
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<tr>
<td><strong>manufacturer’s description</strong></td>
<td>lamp xy</td>
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<tr>
<td><strong>luminaires</strong></td>
<td></td>
</tr>
<tr>
<td><strong>number of luminaires</strong></td>
<td>Number of luminaire per mast</td>
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<tr>
<td><strong>lamp type</strong></td>
<td>vapour lamp, quicksilver, LED, energy-efficient lamp etc.</td>
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<tr>
<td><strong>Power supply</strong></td>
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<td><strong>Luminance performance</strong></td>
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<tr>
<td>spec.1</td>
<td></td>
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<tr>
<td><strong>Switching program lamp 1</strong></td>
<td>Half-night lighting, reduced, full-night lighting, etc.</td>
</tr>
<tr>
<td><strong>Luminance performance</strong></td>
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<td><strong>Switching program lamp 2</strong></td>
<td>Half-night lighting, reduced, full-night lighting, etc.</td>
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<tr>
<td><strong>type mast</strong></td>
<td>attachment conical, attachment out of line, bracket arm conical,</td>
</tr>
<tr>
<td></td>
<td>bracket arm normal, other</td>
</tr>
<tr>
<td><strong>flooring</strong></td>
<td>asphalt, paving, cement, not fixed ground, fixed ground, other…</td>
</tr>
<tr>
<td><strong>result visuell</strong></td>
<td>dings close to the ground, dings &gt; 0,5 m above the ground, disruption next to</td>
</tr>
<tr>
<td></td>
<td>ground, cracks &gt; 0,5 m above the floor, corrosion inext to the floor, corrosion</td>
</tr>
<tr>
<td></td>
<td>&gt; 0,5 m above the floor, other</td>
</tr>
<tr>
<td><strong>Height of light point in meter</strong></td>
<td>Collecting data per 0,5 m</td>
</tr>
<tr>
<td><strong>Wall thickness in mm</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Average of seque into earth in mm</strong></td>
<td>Collecting data per 0,5 m</td>
</tr>
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<td><strong>comment</strong></td>
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Control Cabinet

<table>
<thead>
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<th>content</th>
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<td>site characterisation</td>
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<td>district</td>
<td>specification of cadastral land register – city map</td>
</tr>
<tr>
<td>road</td>
<td>specification of cadastral land register – city map</td>
</tr>
<tr>
<td>fuse protection</td>
<td></td>
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<td>Schütz</td>
<td></td>
</tr>
<tr>
<td>twilight switch</td>
<td></td>
</tr>
<tr>
<td>cables</td>
<td>number, fuse protection, phasing, terminal point</td>
</tr>
<tr>
<td>Electricity meter</td>
<td>Electricity meter no., sort of electricity meter, Electricity meter value, unit (hours, KWh, etc.)</td>
</tr>
</tbody>
</table>

All data which are recorded serve the electronic documentation of asset stock. The data give the basis for decisions regarding the daily work with the illumination systems. You will get a survey and summary about the operating systems and components. To use the recorded data you need a database system. This system should support your requirements regarding data collecting and your individual setup of data fields.

Figure 2
Minimum dimension of data
Which software you will use, depends on different criteria. You can use different software systems for asset documentation:

- Applications for street lighting (management-information system)
- ERP (Enterprise-Resource-Planning), e.g. SAP, Navision, Schleupen other…
- Geographical-information-systems (GIS)
- Development of an own software system
- MS-Excel

Figure 2 shows the minimum requirements for the data collection with a software system. You should not consider using a self-developed software system. The experience shows that these systems are time-consuming and cost-intensive. The advantage of professional applications is that they serve exactly the requirements of street lighting.

Documentation with the systems ERP/SAP or GIS means additional work to define the previous processes, which already exist in an application for street-lighting. You should also consider the updates and support of a professional application. The solution for asset documentation in ERP/SAP or GIS may work, but what about changing processes and updates? The suppliers of these systems don’t have the experience of street-lighting in detail, like the professional software provider of street lighting. With the professional software you will get a system according to your requirements in street-lighting. Updates of the management information system are developed only for this sector referring to practical experiences in street lighting. The supplier of this professional software understands the duties and functions of the technicians outside. Proposals for solutions, which are provided by the specialists working in the field, are easily be included in the software. A specialist has also the experience to transfer difficult and complex data from different server into one system.

A result of this know-how is the actual development of LED. In the beginning the nominal output of LED is for example 35 W and at the end the output will be 51 W. This difference has to be documented. The professional software for street-lighting supports the lower base performance of a luminaire and the different configurations per light point. You are able to select the information about several output performances. After documentation, the software will check the data and run a data correction.

If you use the solution ERP/SAP or GIS it is difficult to reproduce the exact needs of your street-lighting. You depend on that what the system is able to provide, but you can’t adjust it according to your needs. These systems cover a lot of features but don’t focus on the asset documentation of street-lighting. As street-lighting exists of networked information you can’t standardize it’s documentation like it is done in ERP/SAP or GIS systems.

A reasonable way to use the advantages of all systems is, to communicate between the systems via interfaces. GIS for example will be the geographical
component for the luminaire, SAP for planning the material. So you will get the full flexibility of all systems which helps you to create a professional documentation. Here are the base criteria for a software system of street-lighting:

- Functional qualification, reproduction the processes of street-lighting
- Assumption of old data
- Cost and benefit
- Easy integration in the existing IT world
- Communication with other systems like SAP, GIS, DMS, tele management, Mobil-Client

If these criteria are fulfilled you have to identify the features of the software system:

- The system should deliver exact and easy information about a complex lighting-system.
- The customer should be able to decide, which data are important for him and define them.
- Administration of several accounts and locations should be able within one database.
- Limitation of data manipulation for a user/group of users (user A is only able to see data of customer/location A and can only change these data).
- Chronological documentation of the lighting system to identify changes.
- Flexible and simple selection of data.
- Statistical evaluation of every field in a mask/form to identify weak points. (For example: steel mast XY older than 25 years never been checked, controlled.).
- Getting information for planning operations and processes, for example lamp group exchanges, which materials are necessary, number of materials are needed…?
- Analysis lifetime of lamps to get the exact consumption of the luminaires.
- Exact analysis of requirements to plan the yearly disposition.
- Planning and follow up the elimination of faults and support.
- Survey of costs.
- Calculate new scenarios with fictitious data (maintenance cycles of new luminaires, energy saving).
- Description and mapping of switch types (whole night, half night, reduced etc.)
- These information are important to calculate, estimate the exactly power consumption, also for the past time. You can only safe money when you know where.
- To balance the accounts with the customer regarding maintenance cycle, life cycle and burning time.
- To change, alter, copy, export reports and analysis.
- Providing documents, pictures for every site, element, fault, accident etc. no matter which form and size it has. Either you store it in a file system or database.
- You should have the possibility to define and modify the fields and forms and if necessary skipping fields.
- Interface for handheld and pocket PC to finish the orders, to collect data, to read the meter.
- Communication via intelligent interfaces with ERP-systems and standard GIS-systems to provide the exchange of data.
- Connection via web to administrate data.

These are just a few points which can be adapted to your needs (reduced or extended). The most important fact is the support of your processes. The operational processes in a company are growing and being optimized over years. The software should only support your job and adapt your needs. The software should cover the existing, future planned and new processes without expenditure of time and development.

**Maintenance planning and data analysis**

Besides operation control maintenance is a very important but also expensive part in the lighting sector. The focuses are optimization, reducing costs and efficiency enhancement.
With the support of software you can use the lighting data for:

- Budgeting and planning operations based on exact facts
- Calculating potentials for saving expenses with fictitious data
- Analyzing lifetimes to figure out the consumption of lamps
- Establishing costs for planned maintenance
- Identifying weak points with statistical analyses

If you have a look at the unplanned maintenance tasks, you realize that there will be a potential to save expenses. Did you ever try to analyze your faults?

Which type of lamp

- has the highest rate of blackout?
- doesn’t reach the assumed lifetime?

![Figure 4 Statistical evaluations of blackouts](image)

Analyses like this are just possible because of professional and consistent documentation. This fault documentation of blackouts doesn’t need to be elaborated and time-consuming. It just needs to be done consequently!
With the evaluation of data you can realize problems in the lighting inventory and take immediate actions. It is also helpful if you need to discuss about a compensation delivery with your manufacturer because of blackouts caused by a bad quality. The result of a market enquiry shows, that we spend too much money for the maintenance of street lighting. In Germany only 25 percent of lighting assets are optimal maintained.

Documentation with software is essential for planning lamp group exchanges. Only with documentation the regard of maintenance interval is possible. Type diversity and switching time are playing an important role. During a planned maintenance task, like lamp group exchange you can get the exact requirements for the luminaires necessary for the future year. So you will know the future cost for one or two years in advance. This helps you to economize, to plan your investments and manage your lighting business.

Figure 5 Planning of a lamp group exchange – screenshot/example out of luxData

A lot of work in the lighting sector can be optimized with only one software system. The requirements on the responsible person of lighting are rising, like norms (DIN EN 13201) or the introduction of a new financial system. That’s no problem, if you have a professional documentation system for street lighting.

If you work with mobile devices and barcodes, you can improve and optimize the maintenance. Today, we use barcodes everywhere. At the supermarket we see barcodes on the products. If the seller scans the barcode we get information about price, name of product, product manufacturer etc. We need barcodes at railway. Train conductors scan the barcode on the ticket from the internet.

Why shouldn’t we use these advantages for street-lighting? There will be no more paperwork for the technician but mobile devices to show all the information about the light spots, when he scans the barcode. These processes are already possible with luxData.mobile and luxData.mobileApp.
For example handling the repair of damaged street-lighting with luxData and luxData.mobile:

Damages and defects reported by the residents are collected in luxData. This information will be transferred to the mobile device of the technician depending on his location. After he has received the defect report he can start working. An integrated navigation system will help him to get to the right place.

![Figure 6: Screenshots of luxData.mobile](image)

At the site where the fault is, the technician scans the barcode of the lighting. So he gets all information about the configuration and the control cabinets belonging to that site. With the scan of the barcode, the identification of the location will be assigned to the fault. After the fault is eliminated, there will be a scan of laminated sheets to record the operations.

The instruction “lamp is changed” is enough for luxData.mobile, because all other information are provided by scanning the barcode. luxData.mobile rec-
ognizes the site where the technician is and which components are used. The whole supply of services is documented by the technician together with the time needed and the position of the scan. All finished tasks are transferred into the main system of luxData.

The usage of barcodes makes it easy to record the work of the technician. He will not save time but the data which are transferred back to the main system have high quality and are quickly available. This advantage saves time. If you use paperwork instead of mobile devices the technician makes notes. Someone has to put these notes back into the system. Nobody has the time for this work. Therefore information may get lost which are necessary for analysis and evaluations.

After the technician has synchronized the data back to the server, these data will be imported to the main database of luxData. During this procedure the data will be evaluated and checked according to established criteria. This is a big advantage over paperwork because there is no identifying of handwriting, interpretation etc.

Figure 7
Laminated sheets with tasks chosen via barcode
The data of the light spots are already in the system of the mobile device. The data will be checked immediately after the input. This process shows how simple and fast information can be collected. Even additional information about the light spot like coordinates, pictures and evaluation of existing data are possible to add into the mobile device on site.

You find out, that only a management information system developed for street lighting provides you with a comfortable survey and functionality for this segment. With dedicated interfaces you are able to make this management information system to the main system for the whole range of street lighting. Even communication between other systems like GIS, ERP/SAP or control systems are easy to realize.
Financing and operating energy efficient street lighting infrastructures

Matthias Hessling

Street lighting technology in past decades developed steadily, but at moderate pace. For instance, energy efficiency grew slowly, as well as lifetime of lamps and drivers. There was no motivation to replace the existing technology as long as repairs were possible, and energy savings with new equipment were not high enough to justify any large scale investment. This situation has changed completely with LED technology becoming available and now more and more becoming established as first choice technology for almost any street lighting situation. There are several reasons for that:

- Energy prices increased significantly, often (as in Germany) caused by politically motivated changes in the energy mix for electricity generation and by the immense costs of that change towards renewable energy sources. With energy constituting by far the largest cost element of street lighting operations, there is a growing need for more efficient technology.
- The magnitude of energy savings possible by changing to LED street lighting is enormous. Compared to old infrastructures utilising HPM (high pressure mercury vapour) lamps without dimming applications (e.g. in hours of low traffic intensity), LED luminaires with intelligent control easily can save 80% or more. Compared to an “average” street lighting situation, 60–80% energy savings are a reasonable range, and the 60% threshold to receive German state subsidies for the investment into LED luminaires in the years 2011–2013 was rather easy to achieve in the majority of cases, in which HPM lamps were installed before.

![Figure 1](image.png)  
**Figure 1** Timing of investment in LED street lighting
Lifetime expectancy of LED luminaires is high, which means much longer than amortisation time of the investment. While it is discussed a lot, what will happen in let’s say 20 years – whether components of installed LED luminaires will be replaced, or the entire luminaire, and at what cost – until then much less maintenance of LED luminaires is needed as with conventional technology.

The development has passed its early stages, with some typical problems of the establishment of any new technology. In LED lighting this e.g. concerns the colour temperature of LEDs – with “cold white” LEDs being used due to their maximum efficiency despite missing public acceptance, or the sharp cut between bright light on the street and complete darkness off the street – while citizens want to have at least a bit of light in front gardens or facades. Now, while of course further development can be expected (e.g. in terms of energy efficiency), the pace of such development has slowed down.

The same is true for the price. In the first few years, prices dropped to such extent that there was a high motivation to wait for even lower prices. By now, prices have reached a stadium, where no more significant reductions can realistically be expected. In any case, achievable energy savings are much higher than any reasonable expectations for further price reductions. This means that it does not make sense to wait any longer (see figure 1).

A final reason for the establishment of LED street lighting relates to the completely new options for intelligent, adaptive control. It is possible to reduce and rise the level of brightness (“dimming”) without any waiting time. This was impossible with conventional lamps. Thus, LED technology opens new options to control the brightness, e.g. adaptive to the level of traffic, to weather conditions, or in specific situations such as emergency. This is one step towards a “smart city”.

While there is no doubt that changing an old lighting infrastructure to LED technology makes sense, financing the related investment for many cities constitutes a major problem. Even if the responsibility for operating the lighting infrastructure has been transferred to private partners, their contracts typically do not include a modernisation of such scale. New contractual models for the operation of a public street lighting infrastructure are, however, available, and can include the investment into a modernisation of the lighting equipment. Moreover, if an autonomous operation is preferred by a city, or if the responsibility should remain with an established partner, contracting models are available, focusing on delivery, installation and financing of the new equipment. Finally, loans at very low interest rate are available at the moment from KfW, which could be interesting, if a city has no problem with a large loan in its balance sheet.

In the following, some models for operating and/or financing a public street lighting infrastructure, involving a private partner, shall be explained in more detail. The ideal model for a particular city will, however, in most cases be a combination of various models, “tailor made” for the specific conditions and requirements of that city. It therefore is advisable, to discuss and internally agree on those conditions, requirements and specific wishes, before a suitable model is developed and chosen.
In most cases, the involvement of a private partner, or the change to a new contractual model will require a public tender. While this certainly takes some time and effort, experienced consultants are available to carry out a significant part of the work to be done, and it definitively is worth to go that way, because experience has proven that significant cost reductions and better service quality can be achieved at the same time.

The first model (figure 2) shows a standard operations contract between a city and a private operator. There is a wide choice, which tasks should be fulfilled by the private partner. Typically, he will have superior know how, better cost structures and purchasing conditions, and will be paid a monthly or quarterly fee, which can also include aperiodic investments into a modernisation of the street lighting infrastructure. This means a steady financial burden for the city, without any peaks. In more recent contracts, the private partner has to guarantee a certain level of energy savings, including a bonus/malus agreement for higher/lower savings than promised.

If those contracts are tendered, it should be defined carefully how different bids by different bidders are evaluated, and the criterions for such evaluation should be agreed on by the responsible people in the city as soon as possible, thus avoiding dispute at later stages. The price should, of course, be an important, but not the only criterion, others being related e.g. to the quality of service, or the guarantees for energy savings given. A reasonably long contract duration should be chosen, if investments are included in the tasks of the private partner. In such cases, durations between 10 and 20 years are advisable.
In a cooperation model, as shown in figure 3, a city and a private partner found a joint venture company, in which all strategic decisions concerning street lighting are taken. There might even be a supervisory board with members from both sides, including political representatives. Also the management of that company could comprise experts from the city and the private partner, while the latter should receive wide ranging responsibility for all operative tasks, to be carried out by a separate company owned by the private partner. The described model is advantageous if the city wants to be involved more intensively in strategic street lighting matters than in the first model, but it requires a larger size of the city because of additional administrative tasks and costs.

Figure 3  Cooperation model/joint venturer

Figure 4  Contracting with time optimised utilisation of savings
Under the term “contracting” a range of different models can be summarised, the most simple one is shown in figure 4. The principle here is to use the energy savings or a part of such savings, achieved via a thorough modernisation of the old infrastructure, to finance the investment. In figure 4, the focus is on minimising the amortisation period by using the full amount of savings for financing purposes. In figure 5, the city prefers to use part of the savings to reduce the periodic spendings for street lighting. Obviously, this means a longer time needed to finance the investment.

Figure 5  Contracting with immediate savings of operating costs

Figure 6  Contracting with forfeiting
A slightly more complicated model is the one in figure 6. Here, a bank is involved as additional partner. The contractor of the new street lighting infrastructure, who at least is responsible for delivery, installation and financing of the luminaires, optionally for their operation too, sells part of the receivables from the city to the bank. The bank at the same time signs an agreement with the city concerning forfeiting and waiver of defence, which basically means that the bank receives a guaranteed fee directly from the city and therefore is able to finance the investment, done by the private partner, at favourable interest rates normally available for public partners only. Big advantage for the city is that the investment does not cause a burden in its balance sheet (as an investment based on loan would do) and leads to immediate savings in operating costs.

For larger projects, project finance as shown in a simplified form in figure 7 is the preferred model. The private partner does not invest and operate directly, but via a special company (SPV = special purpose vehicle), so that the investment is off-balance for him as well. In several international projects in other businesses, but increasingly in street lighting too, this model is chosen. Setting up of this model is, however, more complex and therefore also more costly. It therefore is suitable for large cities only, and it definitively requires sound advice in several fields.

There certainly are more models available, or combinations of different models, and the figures shown here are rather simplified. It is advisable to consult experts and not just to copy models which might have been applied in a neighbouring city. Whichever model finally is used, it will lead to a new, energy efficient and therefore environmentally friendly street lighting infrastructure with improved lighting quality, long lifetime, lower maintenance costs and significantly lower operating costs in total. The time is right to go for a modernisation and employ one of the various models to finance and operate the new infrastructure now.
Venting keeps IP rating high and maintenance costs low
Why the IP rating of your luminaire won’t last for the life of your light

Henning von Lepel

Bright, reliable LED lighting not only enhances the safety of public and commercial spaces and transit ways but also contributes to the aesthetics and to the quality of life in a city. But over time, environmental factors can degrade the luminaire’s original level of Ingress Protection (IP). This will allow damaging moisture and contaminants to enter the enclosure. The challenge for lighting manufacturers and their customers is to sustain the luminaire’s original IP level, brightness and reliability without escalating maintenance frequency and costs. The most effective solution is a “smart venting element” with a membrane that protects lamp housings against contamination and fluids and provides air exchange and pressure equalization at the same time. Luminaires in outdoor use need to be protected from harsh environmental conditions. The most significant stress factor for the seals of luminaire housings are pressure differences caused by everyday temperature changes.

How can pressure differentials occur?

Changes in outdoor temperature are one of the most common causes of pressure differentials. These changes can be sudden, for instance a strong thunderstorm on a hot summer day, or more gradual over the course of the day or of the year. Either way, they put significant stress on the seals. What is more, direct sunlight can often cause the air inside the luminaire to rapidly heat up, with the resulting higher pressure putting positive pressure on the seals. As temperatures drop again at night, the internal air contracts and creates a vacuum, which draws the seals inward. A drop in temperature from 65°C to 15°C in 11 minutes can create an underpressure of more than 140 mbar inside a housing with 5 liters of free air volume (Figure 1).

Figure 1
Typical calculation of pressure differentials in vented vs. unvented housings
Not only external temperature fluctuations but also temperature changes within luminaires cause pressure differentials. Although LEDs do not get as hot as incandescent lamps, switching a luminaire on and off nonetheless results in significant temperature fluctuations. These are at their strongest immediately after switching, which means that switching luminaires on and off repeatedly puts not only the electronics but also the seals under considerable strain.

Further causes for pressure fluctuations are altitude changes during transportation and the so-called thermal shock, which occurs when, for instance, a hot tunnel light is cleaned with cold water or a high-pressure steam jet. It can also arise when a luminaire encounters snowfall. When luminaires are shipped by air from their manufacturing sites, the lamps will be subject to major changes in altitude, often multiple times when the shipment involves intermediate stops. This means luminaires are exposed to the difference in pressure between a little over 1,000 mbar at ground level and 800 to 850 mbar in the aircraft.

How do pressure differentials and diffusion influence luminaire reliability?

If these pressure differentials are not dissipated, the underpressure within the lamp housing tries to draw the seals inwards, which in turn may eventually cause them to fail. This allows moisture and contaminants such as dust, dirt and other particulates to be drawn inside. If allowed to remain inside sealed enclosures, moisture vapor condenses to liquid water and compromises electronics.

In addition to sudden pressure differentials, moisture can get inside enclosures by diffusion – the process by which vapor moves by natural molecular motion through the enclosure walls. When the moisture vapor enters an enclosure and condenses on the inside, it has no way to escape. Therefore, the liquid water remains inside the enclosure, which could lead to corrosion of the electronics and lenses.

Which industry standards define environmental protection and maintenance of lights for outdoor use?

Two important industrial standards for the environmental protection and the maintenance of outdoor lights are the IEC 60529 and the CIE 154. The IEC 60529 standard confirms that even rugged seals must be protected from repeated stress caused by pressure differentials. If seal performance is compromised, the original IP level will degrade over time in the field. The standard defines that the effects of continuous exposure to weather and the environment are difficult to evaluate, and therefore the choice of material for the enclosure
is as important as the actual IP designation. Attention should also be paid to any gaskets used for the higher IP ratings such that the water cannot readily be drawn past the seal. This is most likely to occur when a warm enclosure is suddenly cooled, causing a pressure drop inside. Of course, non-recoverable degradation occurs even in moderate climatic conditions. Weather changes cause wear that degrades luminaires over time. Designing for, and more importantly sustaining, an IP65 or higher level will extend the life of a luminaire in any environment.

As soon as the IP level drops, lighting users would have to shorten maintenance intervals to keep the same maintenance factor as originally designed (Figure 2).

The international publication CIE 154 confirms that “once the non-recoverable reductions by ageing or soiling have occurred they cannot be brought back to their original condition and replacement of the outer glazing or complete luminaire may be necessary. This is the case with luminaires if they are in, say, dusty or oily atmospheres. In such cases it is well worth considering at the design stage, the use of sealed luminaires of high IP ratings, e.g. IP6X.”

**What is Ingress Protection (IP)?**

The Ingress Protection (IP) rating defines, if a luminaire is able to withstand these stress factors and thus is qualified for outdoor use. This standard defines a system of classifying protection for electronic equipment, devices, or components. IP protection is specified in the IEC 60529: “Degrees of Protection Provided by Enclosures” standard by the International Electrotechnical Commission. This standard specifies the protection an enclosure provides against solid objects and liquids. IP ratings consist of two numbers in the format IPxy: The first number (x) indicates protection against solid objects. The second number (y) identifies the level of liquid protection.
The liquid ratings are not linear. Instead, each number in the rating specifies a different type of protection and does not necessarily meet the previous level of protection (Figure 3). For example, an enclosure with an IPx8 rating protects against a long period of immersion under pressure, but does not address high-pressure spray as defined by IPx6.

**Figure 3** Each number in the IP rating specifies a different type of protection

### What problems arise when IP levels drop?

The failure to equalize pressures within the enclosure has been identified as a root cause of premature failure in outdoor luminaires. Unless relieved, these pressure differentials continue to stress seals. However, the service life of a LED is subject to the reliability of the electronic components and power supply drivers, which altogether make up the lighting system itself. This poses a major challenge to LED systems for outdoor use.

No matter how rugged the seal, its performance will degrade when it is repeatedly stressed by pressure differentials within the enclosure. As seal performance declines, the level of ingress protection degrades accordingly. Field performance no longer meets the “as designed” IP level. With lower Ingress Protection, contaminants can more easily enter the housing. The results are predictable: Moisture that enters and is trapped can cause corrosion and electrical malfunctions; condensation can cloud lenses. Dust, dirt or particulates that enter will accumulate on lenses or reflectors, causing the greatest loss of light. Even routine maintenance is not easy or inexpensive when outdoor lighting is mounted at heights that require lifting equipment, and special safety considerations. How-
ever, if an IP drop compromises one or more aspects of luminaire performance, the frequency and costs of associated cleaning or component replacement will increase dramatically.

**Why does IP drop increase maintenance frequency and costs?**

Consider the example of 10,000 HID streetlights, rated IP65, with a designed maintenance interval of 2.5 years. With a medium level of pollution, the Luminaire Maintenance Factor (LMF) is 0.88. To keep the same LMF when the field performance drops to IP54, the maintenance interval must be shortened to 1.5 years (Figure 2). As shown below in Figure 4, the designed maintenance interval of 2.5 years requires maintaining 4,000 lights per year. When the IP drop shortens the interval to 1.5 years, 6,667 lights per year must be maintained. This increases maintenance costs by 60 percent.

**How can pressure differentials be equalized?**

The key to maintaining the original IP rating and avoiding higher maintenance costs is pressure equalization. To maintain constant pressure inside a luminaire it is crucial to allow air to flow freely in and out of the luminaire. The challenge is to block water and contaminants in doing so. Most types of seals to achieve this goal have multiple drawbacks as explained below:

- Labyrinth seals are completely permeable to particles, insects, and water.
- Rugged seals, additional bolts, thicker housings or potting compounds for hermetically sealing the device require the use of non-permeable materials, and are relatively expensive. Moreover, these make the device heavier, extremely difficult to open under negative pressure and almost impossible to repair.

![Figure 4](image)

*A maintenance interval reduction of a year can cause a cost increase of up to 60 percent*
Felt elements and sintered vents address the pressure differentials, but they can become blocked by water and contaminants.

A mechanical valve is a one-way solution from inside to outside, which means it cannot prevent a vacuum.

A “breathing” membrane solution protects the integrity of the electronics by allowing air and moisture vapor to flow freely into and out of sealed enclosures. At the same time, it serves as a barrier to prevent contaminants such as dirt, dust and sand from entering the enclosure.

**How do luminaire housings “breathe”?**

Two-way “breathing” membrane solutions exist in various designs and with multiple membrane types. Comprehensive solutions use ePTFE membranes. They are ideally suited to venting applications because of their unique microstructure. The PTFE raw material is stretched in a specially designed process to create a membrane with very fine pores. ePTFE’s microstructure is open enough to allow gas molecules and vapor to pass through it easily, but the openings are so small that liquid and other particulates are repelled. Equalizing pressure using an ePTFE membrane vent reduces the potential for moisture vapor to condense on lenses and reflectors, and increases the service life of seals. An important side effect for LED luminaires is, that hydrogen sulfide is released this way.

**Important consideration: Hydrogen Sulfide**

Hydrogen sulfide is given off especially by inexpensive EPDM seals produced using sulfur vulcanization where not all the sulfur atoms were 100 percent cross-linked. Sulfur vulcanized nitrile butadiene rubber (NBR) or other components containing sulfur can also give off hydrogen sulfide. This substance causes corrosion in LED luminaire components such as silver-plated lead frames, which could impact electrical contacts with the wire bond or die bond.

**What characteristics are required for an effective membrane solution?**

ePTFE is not only ideally suited for venting applications due to its unique microstructure but also because of its high chemical and temperature resistance. The material is extremely hydrophobic (water resistant) thanks to its low surface tension, which means that any water droplets on the surface are unable to penetrate the membrane structure. The membrane is also oleophobic (oil resistant) and repels liquids with low surface tensions, such as cleaning detergents.
ePTFE membranes are also resistant to almost all industrial chemicals. The only substances currently known to compromise ePTFE membranes are elemental sodium, other elemental alkali metals, fluorine, metal hydrides in concentrations greater than 80 percent, and amines and imines when exposed at temperatures exceeding 260 °C. Another advantage of ePTFE is its general resistance to extreme temperatures that are far beyond the operating temperatures of outdoor lighting applications.

How does a membrane affect humidity and pressure in a luminaire?

Comparing the relative humidity inside luminaires after a standard IPX5 water ingress test demonstrates the significance of pressure differentials. The relative humidity in the unvented luminaire was significantly higher than in the vented luminaire. Over the course of ten days, the relative humidity in the unvented luminaire almost always remained at around 100 percent (Figure 5).

This indicated condensation inside the luminaire was caused by water entering during the test. Although the relative humidity in the vented luminaire rose immediately after each cold water shock test, it decreased again relatively quickly and there was no evidence of condensation.

![Figure 5](image)

*Figure 5  The unvented housing shows relative humidity of 100 percent, indicating condensation*

A further test, conducted outdoors over a period of five years south of Munich, demonstrated the longer service life of vented enclosures. Five housings were tested: two with no vents, one with a side vent, one with a top vent, and one with two vents (one on each side), as shown in Figure 6.
The testing showed that the pressure differential in the unvented units ranged from -150 mbar in both to +131 and +147 mbar respectively. A significant amount of condensation was also detected. In the vented units, the maximum pressure measurements fell to ±40 mbar with a top vent, ±30 mbar with a side vent, and just ±4 mbar with both vents (Figure 7). This is an impressive demonstration of how effective these venting systems are at equalizing pressure.

Figure 6  Long-term test with five housings

Figure 7  Long-term study of pressure differentials in electronic housings
In addition, no condensation was detected in the vented housings, and neither was the ingress of water or dust (Figure 8). Further testing showed that the GORE® Protective Vents were fully functional even after five years of outdoor operation.

Figure 8  Long-term study demonstrates how venting prevents condensation

Roundup: How do venting solutions extend the service life of outdoor luminaires?

Pressure differentials compromise housing seals. Not taking this into account when designing luminaires can reduce the service life of the light source, the power supply drivers and other electronics. The ingress of water through damaged seals also leads to condensation on lenses and reflectors that can decrease light efficiency and the aesthetic quality of the luminaire. Also maintenance costs can increase dramatically if seals are compromised and therefore the IP rating of the housing diminished. As demonstrated, integrating an ePTFE vent into the housing equalizes pressure by allowing continuous airflow, prevents the ingress of water and minimizes maintenance costs over time.

You will find more information about the long-term study, which Gore performed with enclosures in outdoor environment, at www.gore.com/5-year-study.
Adaptive road lighting
Is 2-LID road lighting for dry and wet roads useful?

Andreas Walkling & Christoph Schierz

The field experiment presented in this article was conducted as part of the Thuringian Join Project ‘CoLight’ (Corporate in Lighting). This Research and Development project was funded through the Thüringer Aufbaubank (TAB) and the European Regional Development Fund (ERDF).

1 Introduction

Rain occurs frequently in Central and Western Europe. In Great Britain for example, one can expect an average of at least 133 rainy days each year. On wet roads, the reflection behaviour changes significantly, and with it, the distribution of luminance. The resulting loss in visibility increases the risk of accidents at night. A study commissioned by the German Federal Highway Research Institute on the influence of weather on accidents showed that on wet roads, accident rates are approximately 19\% higher than on dry roads [1].

In the interest of road safety, consistency in visibility for dry and wet roads is needed [2]. The basic requirement cannot be fulfilled with conventional road lighting in most European countries because it is solely designed for dry roads. Generally speaking, this leads to a safety gap for wet conditions, as the EN 13201-2 falls below the recommended overall uniformity of luminance ($U_{o,w}$) of 0.15 ($w = \text{wet}$) [3]. In addition, very bright, reflective strips of light are created on the road, causing reflection and further degradation of visibility.

The critical reduction in overall uniformity of wet roads can be prevented with lights, in which the light intensity distribution (LID) reduces the specular reflection between the light source and the driver, and in return amplifies the luminous intensity in other directions. Therefore, this better adapted LID differs from conventional road lighting, in which the optimized luminance is exclusively for dry conditions [4]. Such fixed road luminaires containing an additional ‘wet road light’ will be referred to here as 2-LID lighting.

A useful local adaption of light distribution for a variety of environmental conditions (for example city, highway, fog, rain or snowfall), using the help of multi-LID-systems, has already been adapted for automotive headlights. This so-called bad-weather light reduces the glare created by the driver and illuminates the roadside in order to improve the visibility conditions seen with bad weather [5].
2 Cons: 2-LID lighting is not useful

The most important counter-argument against 2-LID lighting is the allegedly low amount of precipitation. However, if one compares the 855 mm of rain annually occurring with wet weather in Great Britain for example to the 750 mm from the CIE’s rain-reference country Denmark, this argument does not appear to be applicable [6]. The same is also true for other European countries such as France or Germany. Even during the cool and damp seasons, when the average rainfall in France and/or Germany is up to 30% lower (see Figure 1), the wet conditions (W-classes) year-round are nevertheless applicable. The reason: The drying time in the cold and wet seasons is much longer than in summer.

This means the roads are not only wet during rainfall, but also during the following dry time, in which a completely wet surface in spring or autumn, when the amount of dark hours is particularly high, can last for days. In this case, the reflection behaviour for dry roads (C-classes) loses relevance [2]. In this respect, this counter-argument is not justified.

Another important counter-argument is that the conventional 1-LID lighting can be dimmed without hesitation in wet conditions. The significant increase in average luminance levels ($L_{\text{ave}}$) serves as an additional justification for dimming lights on wet roads. At the same time, it is not noted that the overall uniformity ($U_{o,w}$) required on wet roads is not fulfilled.

This leads inevitably to very small minimum luminance values ($L_{\text{min}}$) and very high levels in the visibility field of the driver. Large and dark, camouflaged surface areas create a higher direct glare, because with this view the disability glare will have more of an effect. Bright reflective strips, however, create a higher indirect glare and simultaneously reduce the detectability of obstacles in dark, camouflaged zones.

Figure 1
Average yearly rainfall (Measure: 1961–1990) [7]
To illustrate a typical European traffic road (luminaire spacing $S = 40$ m, mounting height $H = 8$ m, lighting class ME3c) the numerical values are shown in Table 1, in which the results are yielded from the use of conventional 1-LID lighting (without ‘wet road lights’). The critical case shown in the column ‘Situation 3’, demonstrates that the required $U_{o,w}$ is not met, even when the lights are dimmed by 50%. Therefore, the difference in luminance (here from 1:35) between $L_{\text{min}}$ and $L_{\text{max}}$ is problematic in terms of visual performance. In practice, this means when utilizing 1-LID lighting, the lighting levels on wet roads should not be reduced. In this respect, the second counter-argument is also invalid.

<table>
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<th></th>
<th>Minimum/maximum values for class ME3c</th>
<th>Situation 1: dry road</th>
<th>Situation 2: wet road</th>
<th>Situation 3: wet road, 50% dimmed</th>
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</tr>
<tr>
<td><strong>r-table</strong></td>
<td>CIE C2</td>
<td>CIE W4</td>
<td>CIE W4</td>
<td></td>
</tr>
<tr>
<td><strong>$q_0$</strong></td>
<td>0.07</td>
<td>0.166</td>
<td>0.166</td>
<td></td>
</tr>
<tr>
<td><strong>LID</strong></td>
<td>1-LID</td>
<td>1-LID</td>
<td>1-LID</td>
<td></td>
</tr>
<tr>
<td><strong>$H$ in m</strong></td>
<td>8</td>
<td>8</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td><strong>$S$ in m</strong></td>
<td>40</td>
<td>40</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td><strong>Overhang in m</strong></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td><strong>Tilt in application in °</strong></td>
<td>5</td>
<td>5</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td><strong>$L_{\text{ave}}$ in cd/m²</strong></td>
<td>1.0</td>
<td>1.42</td>
<td>3.09</td>
<td>1.54</td>
</tr>
<tr>
<td><strong>$U_o$</strong></td>
<td>0.4 (dry) / 0.15 (wet)</td>
<td>0.55</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td><strong>$L_{\text{min}}$ in cd/m²</strong></td>
<td>0.4</td>
<td>0.82</td>
<td>0.38</td>
<td>0.19</td>
</tr>
<tr>
<td><strong>$L_{\text{max}}$ in cd/m²</strong></td>
<td>2.36</td>
<td>13.52</td>
<td>6.76</td>
<td></td>
</tr>
<tr>
<td><strong>TI in %</strong></td>
<td>15</td>
<td>14.5</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td><strong>SR</strong></td>
<td>0.5</td>
<td>0.54</td>
<td>0.54</td>
<td>0.54</td>
</tr>
</tbody>
</table>

**Table 1** Comparison among varying lightings of 1-LID lighting on dry and wet roads. **Note:** The abbreviation ‘n.a.’ means not applicable. Reason: The TI-formula is not applicable because the luminance distribution is too non-uniform on wet roads [8].

### 3 Pro: 2-LID lighting is useful

An important argument in favour of using 2-LID lighting is that the conventional luminaire spacing does not have to be shortened if one is to fulfil the dry and wet conditions. Those with 1-LID lighting would only achieve the required value of $U_{o,w}$ by shortening the luminaire spacing. Table 2 depicts this situation for the previously calculated example. The column ‘Situation 1’ shows the
general case in which the $U_{o,w}$-requirement is not met. This means in practice that the conventionally laid 1-LID-systems do not light according to standards. Moreover, the comparison between situation 1 and 2 shows that the $S$ of 1-LID lighting would have to be unacceptably shortened by some 20% to 33 m, in order to comply with $U_{o,w}$. In addition, this ‘shortened’ lighting would be oversized because $L_{ave} >> 1 \text{ cd/m}^2$ and $U_o >> 0.4$ (see situations 2 and 3).

<table>
<thead>
<tr>
<th>Road width in m</th>
<th>Minimum/maximum values for class ME3c</th>
<th>Situation 1: wet roads</th>
<th>Situation 2: wet roads</th>
<th>Situation 3: dry roads</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>6.5</td>
<td>6.5</td>
<td>6.5</td>
</tr>
<tr>
<td>r-table</td>
<td></td>
<td>CIE W4</td>
<td>CIE W4</td>
<td>CIE C2</td>
</tr>
<tr>
<td>$q_0$</td>
<td></td>
<td>0.166</td>
<td>0.166</td>
<td>0.07</td>
</tr>
<tr>
<td>LID</td>
<td></td>
<td>1-LID</td>
<td>1-LID</td>
<td>1-LID</td>
</tr>
<tr>
<td>$H$ in m</td>
<td></td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>$S$ in m</td>
<td></td>
<td>40</td>
<td>33</td>
<td>33</td>
</tr>
<tr>
<td>Overhang in m</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Tilt in application in °</td>
<td></td>
<td>5</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>$L_{ave}$ in cd/m$^2$</td>
<td>1.0</td>
<td>3.09</td>
<td>2.57</td>
<td>1.33</td>
</tr>
<tr>
<td>$U_o$</td>
<td></td>
<td>0.4 (dry) / 0.15 (wet)</td>
<td>0.10</td>
<td>0.15</td>
</tr>
<tr>
<td>$L_{min}$ in cd/m$^2$</td>
<td>0.4</td>
<td>0.38</td>
<td>0.41</td>
<td>0.93</td>
</tr>
<tr>
<td>$L_{max}$ in cd/m$^2$</td>
<td>13.52</td>
<td>9.76</td>
<td>1.92</td>
<td></td>
</tr>
<tr>
<td>$Tl$ in %</td>
<td></td>
<td>15</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td>$SR$</td>
<td></td>
<td>0.5</td>
<td>0.54</td>
<td>0.66</td>
</tr>
</tbody>
</table>

Table 2  Comparison among varying illuminations for 1-LID lighting on dry and wet roads

Thus, the shortening of the spacing between luminaires for 2-LID lighting is not necessary. Table 3 provides a summary of this benefit. The optimized $S$ of 40 m for dry roads can be maintained on wet roads because the $U_{o,w}$-requirement is fulfilled. Another advantage is that the edge of the road is illuminated brighter as would be with automotive headlights (surround ratio ($SR$) increases from 0.54 to 0.73).

‘Situation 2’ also shows that the luminance ratio of 1:23 between $L_{min}$ and $L_{max}$ precipitates smaller than in the 1-LID lighting with 1:36 (according to Table 1), and is less problematic. In practice, this means that when using the 2-LID lighting the lighting levels can be reduced for wet conditions, even if the luminaire arrangement is staggered. In this respect, this pro-argument is justified.
The most important argument in favour of the introduction of 2-LID lighting is the increase in safety from better visibility on wet roads, which is mainly influenced by overall uniformity. The reason: The driver’s adaptation level is determined less by the average road luminance ($L_{\text{ave}}$) but rather by the small, bright reflective strips and large, dark camouflaged areas within the visual field of the carriageway [4].

<table>
<thead>
<tr>
<th>Minimum/maximum values for class ME3c</th>
<th>Situation 1: dry roads</th>
<th>Situation 2: wet roads</th>
<th>Situation 3: wet road, 50% dimmed</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Road width in m</strong></td>
<td>6.5</td>
<td>6.5</td>
<td>6.5</td>
</tr>
<tr>
<td><strong>r-table</strong></td>
<td>CIE C2</td>
<td>CIE W4</td>
<td>CIE W4</td>
</tr>
<tr>
<td><strong>$q_0$</strong></td>
<td>0.07</td>
<td>0.166</td>
<td>0.166</td>
</tr>
<tr>
<td><strong>LID</strong></td>
<td>2-LID</td>
<td>2-LID</td>
<td>2-LID</td>
</tr>
<tr>
<td><strong>$H$ in m</strong></td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td><strong>$S$ in m</strong></td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td><strong>Overhang in m</strong></td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Tilt in application in °</strong></td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td><strong>$L_{\text{ave}}$ in cd/m²</strong></td>
<td>1.0</td>
<td>1.42</td>
<td>1.37</td>
</tr>
<tr>
<td><strong>$U_o$</strong></td>
<td>0.4 (dry) / 0.15 (wet)</td>
<td>0.55</td>
<td>0.21</td>
</tr>
<tr>
<td><strong>$L_{\text{min}}$ in cd/m²</strong></td>
<td>0.4</td>
<td>0.82</td>
<td>0.32</td>
</tr>
<tr>
<td><strong>$L_{\text{max}}$ in cd/m²</strong></td>
<td>2.36</td>
<td>7.4</td>
<td>3.7</td>
</tr>
<tr>
<td><strong>$TI$ in %</strong></td>
<td>15</td>
<td>14.5</td>
<td>n.a.</td>
</tr>
<tr>
<td><strong>SR</strong></td>
<td>0.5</td>
<td>0.54</td>
<td>0.73</td>
</tr>
</tbody>
</table>

Table 3 Comparison among varying illuminations of 2-LID lighting on dry and wet roads

In addition, a separate field experiment with a test road and participants was carried out in Ilmenau/Germany. The straight road was partially lit ($S = 30$ m, $H = 8$ m, lighting class ME2 with dry and wet carriageway, colour temperature = 2,000 K). For the investigation, a controlled highway length of approximately 300 m was watered (see Figure 2). To represent visual objects, standard grey boards (20 cm × 20 cm) with different reflective degrees (0.03, 0.15, 0.2 and 0.3) were used, which are valid as classic obstacles in road lighting research. The objects were randomly distributed and placed in nine positions within the EN-assessment field. The experiments were performed with a maximum of 13 participants per trial run per evening. None of the subjects were older than 40 years of age. The visual task by the trial group was to evaluate, in a limited observation pool, the visibility of each obstacle on a four-point scale.
As seen in Figure 3, the results show that with an increase in overall uniformity ($U_{o,w}$), the visibility of objects or critical obstacles on wet carriageways in the assessment field (i.e. for all object positions and observer judgments) increases on average from 2.4 to 2.7. Thereby the 50% increase in the overall uniformity is comparable with a change from 1-LID lighting to 2-LID lighting. The vulnerability between dry and wet lit roads, as mentioned in the introduction, is thus reduced (not closed), making the most important pro-argument seemingly correct. However, in order to completely fulfil the basic requirement from Kebschull (i.e. same visibility for both dry and wet roads) [2], a further increase of $U_{o,w} = 0.15$ appears to be advisable.

Figure 3  The average values with their standard error of visibility of objects versus the object position. Parameter is the overall uniformity. The object positions comprise three lateral rows (‘A’ = 65, ‘B’ = 75 and ‘C’ = 85 m observational distance) and three longitudinal rows (‘L’ = left, ‘M’ = centre and ‘R’ = right). The visibility scale used values from 0 (invisible), 1 (very poor visibility), 3 (moderate visibility) and 5 (very good visibility). The average observer position in this case is centred on the right lane.
4 Conclusion

The previous chapter demonstrates that the influence of moisture in several key European countries, from a technical lighting perspective, is similarly as high as that of the CIE reference-country Denmark. A separate field experiment showed that the influence of the overall uniformity ($U_{o,w}$) on the visibility of objects on wet carriageways is unmistakably present, and that the minimum value 0.15 should therefore be respected.

The fact that the conventional 1-LID road lighting is used and dimmed without hesitation on wet roads shows the critical case in which visibility conditions inadmissibly worsen. Either one should avoid dimming if possible or logically use the 2-LID lighting (with additional ‘wet road light’) in order to close the safety gap and to similarly standardize lighting and dimming.

An essential dynamic-adaptive 2-LID road luminaire with LED and sensor technology has already been implemented as a technical prototype [9, 10].

5 Literature


[10] Li, C. et al.: Freeform reflector design for LED street lighting. SPIE 2011 Optics + Photonics, USA, August 2011
Cariboni group lights up the municipality of Lichtensteig (Switzerland) with KAI. Extremely compact, optimized and manufactured specifically to accommodate LED sources of latest generation. Available in three sizes Small, Small X and Medium. Different optical systems, efficient and with high performance, ensure the use of KAI for the lighting of urban and suburban roads and pedestrian and cycle paths. Possibility of replacing the optical system. 

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Vorwort zum Buch


Der Autor dankt allen Unternehmen, die durch die Bereitstellung von Informationen und Firmenunterlagen zum Gelingen dieses Buches beigetragen haben. Den Mitarbeiterinnen und Mitarbeitern des Verlage EW...
The field of municipal street and outdoor lighting has been undergoing significant change for some time now. Not least the introduction of LED lighting has completely revitalised the development of new luminaires, electronic control gear and components.

However, many decision makers with a responsibility for lighting will find the huge array of products on the market as well as the associated flood of technical data quite challenging. The only way to assess the numerous differing claims is to acquire dependable expert knowledge on the topic. This technical street and outdoor lighting manual is designed to assist users in the process of obtaining an overview of the current state of the art.

A select group of lighting industry experts and users of lighting technology has contributed to this book with the aim of explaining the complex topic of lighting. It is designed to support employees of municipal utility companies and energy providers, representatives of town councils as well as planning and engineering companies in making decisions regarding current projects.